"MAINTENANCE OF THE CULTURAL HERITAGE CONSTRUCTIONS FROM THEIR COMPREHENSION AS A WHOLE" - MACH

Funding scheme: collaborative projects (small or medium-scale focused research projects)

Theme 6. Environment (including climate change)

ENV.2007.3.2.1.1. Damage assessment, diagnosis and monitoring for the preventive conservation and maintenance of the cultural heritage

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6- SMARTEC	SMARTEC SA, Manno, Lugano	SWISS
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Proposal

1: Scientific and/or technical quality, relevant to the topics addressed by the call
1.1 Concept and objectives

Explain the concept of your project. What are the main ideas that led you to propose this work?
Describe in detail the S&T objectives. Show how they relate to the topics addressed by the call. The objectives should be those achievable within the project, not through subsequent development. They should be stated in a measurable and verifiable form, including through the milestones that will be indicated under section 1.3 below.

There is an increasing awareness of the urgent need to share scientific knowledge and to adopt common methodologies and materials for the protection and conservation of cultural heritage at a European level. In fact, a scientific approach is nowadays essential as preliminary basis to guarantee a proper planning of ordinary and extraordinary maintenance works, and to assure their efficacy and durability. Only thanks to a sound scientific knowledge of the structural characteristics and materials constituting the artefact, of its environmental and conservation conditions, these conservation/restoration works can be successfully carried out.
Unfortunately the great experience developed in this field by the different European countries, for the time being can not constitute a common background because there are too many differences not only in the methods of analysis, but also in the terminology used. A specific European standardisation activity in the field of conservation of Cultural Heritage is essential to acquire a common unified scientific approach to the problems relevant to the preservation/conservation of the Cultural Heritage.

The General Objective of the Project is to establish *Damage Assessment, Intelligent Monitoring, Simulation and Risk Analysis Tools* for the protection and conservation of Europe's cultural heritage constructions endangered by natural aging and foreseen future climatic changes of the Earth (i.e. "Global Warming"). The creation of a European Platform for web-applications and services, but upon all, for **networking** of experts to attack these problems in a **wholistic** manner will contribute to the diffusion and adoption, in the field of Cultural Heritage, of the preventive conservation and scheduled (or "intelligent") maintenance **concept.** The development of these tools lying on a common web-platform is a crucial and strategic point for the future sustainable preservation of monumental heritage. Short term identification and correction of defects and local structural damage and failures in monumental buildings, after a restoration has been finished, will prevent major non-reversible damage and partial or total collapse which may lead to enormous loss on investments. In fact, when regular maintenance is carried out the conservation costs will be lower in the long run and non-reversible damage will be avoided.
This ambitious objective will be achieved with the design of specific **Decision Supporting Tools (DST),** lying on the European platform (called Mach Platform - MaP) that will be easily accessible in the future for the stakeholders and policy makers of the European Monumental Heritage and that is based on the comprehension of decay and failure processes of a **Monument as a Whole** (wholistic approach).
These tools refer to the development/improvement of i) cost/effective **Stationary** Fiber Optics Sensors (FOS) and **Wireless Sensors** (SWS) and **portable** non-destructive (NDT) and minor destructive (MDT) technologies for failure, damage assessment and material monitoring with high resolution, accuracy and reliability; ii) numerical simulation tools and iii) diagnostic and risk analysis tools. The monumental benchmark test sites on which the **DST** will be developed and validated will be selected taking into consideration, the diversity of the nature of that heritage (location, stylistic, constructive and past interventions) and the diversity of risks to which it is exposed to: *environmental and climatic impact* (weather, pollution) *on foundation and structures* (masonry and timber); *natural or man-made hazards* (earthquake, flooding, traffic and visitors); *immovable and movable heritage materials that the monument may host* (stones, bricks, mortar and wall paintings).
The data acquired in specific monitoring campaigns, using the developed portable NDT/MDT technologies and the stationary wireless sensors, will be used to feed the **Simulating Tools** (ST) for the different materials and elements and for the virtual monument model, avoiding subjective rules for periodical interventions leading to high costs and high risk of non-reversible failures The ST will supplement the final **Decision Supporting Tool** *(Damage Assessment, Intelligent Monitoring, Simulation and Risk Analysis - **DAMSRA** of a Monument as a Whole).*

The DST developed will integrate the stationary and new NDT/MDT methodologies for single cause/effects damage evaluation (static and dynamic performance) and the "whole" risk analysis for hazards on structural, non-structural items and environmental constraints. This shall be open to such an extent that the end user can apply it on other monuments in different geographical and environmental contexts.
The integration of different disciplines and the collaboration between expertises coming from different countries is of crucial importance to develop valid protocols at a more generalised level than for just a single nation. Each individual situation is characterised by different construction techniques, different environmental contexts, and specific conservation and/or restoration practices, which nonetheless the DST must encompass. The consortium has highly specific and interdisciplinary competencies (scientists, conservators) and encloses SMEs specialised in the development of innovative diagnostic and monitoring instruments.

1.2 Progress beyond the state of the art

Describe the state of the art in the area concerned, and the advance that the proposed project would bring about. If applicable, refer to the results of any patent search you might have carried out.

The MACH project intends to incorporate in its activities and exploit some of the successful outcomes of previous EC funded Projects dealing with the conservation of monumental buildings (**ANNEX 1**). These have produced a huge amount of information and data but without an effective dialog and integration. It is the moment for advancing a step more in the investigation on the Cultural Heritage modifying the used conventional research criteria until now.
As preliminary considerations, that will be further discussed and approved in the first months of the project, on the basis of the experience made by some partners in previous projects the following outcomes will be inserted in the diagnosis and monitoring of the monumental bench mark sites: some of them will be adopted as such (Radar and active thermography - Software tool for the 3D digitalization of artefacts and architectures), others will be improved (COMPASS - MDDS, DIAS tools, HISTOCLEAN - Surface measurement technology), while few will be developed specifically for the objective proposed (WSN Wireless Sensor Network, HD - Hole Drilling).
An extended examination of the nowadays applied techniques and methods for the scientific study in the Monumental Heritage field, made by some partners and coming from literature, (**ANNEX 2**) has evidenced frequent limited approaches focused on individual materials (stone, plaster), specific problematic (salt - biodeterioration) or targeted intervention procedures (waterproofs, laser cleaning) with the elaboration, in few cases, of decay processes evaluating mathematical models and risk or damage assessment expert systems. All these achievements mostly constitute a specific and isolated part of the problems that can be present in a Monument.
The progress of knowledge of such researches will derive from studying the most relevant parameters affecting the long time behaviour of a Monument as a Whole.

Monitoring of a Construction of the Cultural Heritage "as a whole" calls for accounting for many technologies, knowledge and experience, sometimes having no common denominator and belonging to really separate fields of science. This is due to the very complex nature of a monumental building and its context and requires involvement and close collaboration of many specialists.
Monitoring is used in the meaning of systematically periodical surveillance of Cultural Heritage assets, by the use of stationary or portable reliable diagnostic tools. The intention is to identify changes in structural and superficial physical-chemical conditions of monumental building (as a whole) over time and environmental changes. Monitoring is based on assumptions of cause and effect and the results help identify potential threats and development trends in order to define a Risk Assessment Map and to facilitate maintenance management decisions. The first step is to identify the most appropriate parameters for "qualify" the state of conservation of a cultural artefact in order to understand it. The second step is to select the most efficient (cost/benefit) device to determine the identified parameter. The third step is to establish the most suitable protocol (time interval and methodology) for monitoring the identified parameters. The need for comprehensive cultural heritage surveillance and accessible monitoring data has been particularly outlined in the last years with emphasis about a growing need for standardised monitoring systems. The monitoring aim will be concentrated on potential threats such as: "structural failures" "loss of materials", "state of preservation", "environmental influence", "colour

changes" and "texture modification". The quality of monitoring data must be essentially based on "precise value" in order to be able to derive trends estimation over time for scheduling a sustainable maintenance programme.
High costs appear to be the worst limiting factor in monitoring in CH management and protection in general. Among the concrete hindrances caused by low funding is the feasibility of a holistic and large scale approach. Very often a low number of monitoring areas and/or objects can be included. CH heritage objects are often listed- "ranked by importance" - leaving the less important to decay. There is a need for diffuse the monitoring principle to a larger set of CH assets. This objective can be achieved with new or improved non destructive technologies and working methods for the damage assessment, diagnosis and monitoring of the cultural heritage focussed on their reliability, autonomy and value for money.
Thus, the expected impact of the project is to set-up effective cost-efficiency systems in order to reduce the conservation costs prolonging the time lapse for future conservation interventions and scheduling a correct maintenance programme. The establishment of a common monitoring framework is based on the improvement of methodological tools for data collection and analysis supported by well established guidelines.
The project has an high innovative content as much by the progress of the knowledge derived from the integration, in a common web driven MACH platform, of very different type of data (stylistic, historic, graphic, digital, analogic) coming from the execution of the jointly research works and daily practice of care and maintenance interventions. The new points are: - the monument is considered as a whole in order to understand it; - application of the performance in use and monitoring concept; - application of effective techniques and methods for in situ damage characterisation, normalised through the redaction of guidelines and recommendations; - built of 4D virtual model of monuments; - elaboration of the risk assessment and the mathematical models to interpret the rate of decay of a monument and to establish diagnosis and the decision criteria for the intervention; - the SMEs participants will prove the results in their scheme of usual work.
The final objective - *the comprehension of decay processes of a Monument as a Whole*, for the diagnosis, monitoring and the scheduled maintenance, will be developed and validated using some monumental buildings, located in different geographical areas and environmental context, as benchmark test sites for conservation problematic. These will be monitored through the use of both the stationary wireless sensors network and the portable new diagnostic technologies (some of them could be patented). The data, once filtered will can be observed in real time on the 4D virtual model. Last generation of analytical and numerical methods (*Probabilistic Risk Assessment Model)* will be used in order to evaluate the damage state and to assess the residual life*,* together with a model-free statistical analysis of continuous monitoring data to extract novelty functions as possible indicator of changes in the weathering behaviour and define the more cost effective maintenance interventions (*Criteria of Sustainability*).
The knowledge will be validated by all partners, Institutions and SMEs, involved in the Conservation Process, in collaboration with the future MACH Mirror Group.

The partners have indicated to select as main case study some historical buildings placed in the old city centre of Siracusa (Italy), the Island of Ortigia (Unesco site, belonging to the Province of Siracusa, which, in its letter of support to the MACH project, declares that all selected buildings are accessible –ANNEX 3). This choice is focused on the wholistic approach: to consider a monument not as extracted from its context, studied as a stand-alone object, but inserted in its surrounding environment and city fabric, a monument is something more complex, stratified and articulated than just a simple series of problems. Furthermore, we can find in this area the most frequent conservation problematic (structural, seismic, vibrations, stresses, cracks, humidity, biological growth, saline attack, traffic, pollution) and selection of materials (stone, bricks, mortar, metal, timber and wall paintings). To deal with these different aspects various specialist competences, both knowledge-based and technology-based, have to be merged in an operative team. The more complex the target, the more integration we need to establish, in order to cope with the final objective.
Other three monumental benchmark sites will be considered in the project located in three different geographical areas.

The project intends to support the CEN and RILEM Standardisation organisms in the field of definitions and terminology, methods of testing and analysis, characterisation of materials and deterioration processes of

movable and immovable heritage, and the products and technologies used for the planning and execution of their conservation, restoration, repair and maintenance. Moreover, the definition of recommended methodologies and procedures could be strengthen and diffused through the *European Construction Technological Platform*, *Focus Area Cultural Heritage* (ECTP - FACH), which should promote the exchange of information, avoiding the risk of duplication and fostering synergy between the European experts and specialists involved in the conservation activities. The material produced in the project will be structured and used for training purposes in seminaries and in higher academic courses.
In a concrete way the project, after a ranking of the capacities of each technique or method to solve each problematic, will develop specific recommendations for a reduced amount of diagnostic technologies, but very proven, with the aim to quantify exactly the parameters needed for establish the risk assessment of a monument as a whole and schedule its preventive maintenance.

1.3 S/T methodology and associated work plan

A detailed work plan should be presented, broken down into work packages 1 (WPs) which should follow the logical phases of the implementation of the project, and include consortium management and assessment of progress and results. (Please note that your overall approach to management will be described later, in section 2).
Please present your plans as follows:
i) Describe the overall strategy of the work plan.
ii) Show the timing of the different WPs and their components (Gantt chart or similar).
iii) Provide a detailed work description broken down into work packages:
iv) Provide a graphical presentation of the components showing their interdependencies (Pert diagram or similar)
Note:
1 A work package is a major subdivision of the proposed project with a verifiable endpoint normally a deliverable or a milestone in the overall project.

Overall strategy

To accomplish the general objectives, the following steps are intended to be fulfilled:

- Management and coordination of the project (WP1).
- Careful selection of case studies, identification of their geometry, architectonic typology, environmental context and problematic. Construction of a virtual 3D model (WP2).
  Evaluation of previous developed diagnostic and monitoring systems coming from literature, experience of partners and past EC funded projects (WP3). The different data (geometrical, historical, analogical and digital - 3D) originated in the project will be harmonised and integrated in the innovative Web Driven Interactive MACH Platform (WP4).
- Development and improvement of the most innovative diagnostic techniques in order to obtain the most valid parameters for evaluate the damage of a Monument as a Whole; together with the design and development of wireless sensor network (WSN) systems (WP5).
- The monumental benchmark sites selected will be monitored “as a whole” for a period of about 3 years with time intervals of 1 year, through the use of the developed WSN for continuous monitoring and of the portable diagnostic tools for some meaningful time or climatic-dependent parameters (WP6).
- The verified monitoring procedure for a “Monument as a Whole” (parameters, protocols, techniques and methods) will be standardised (recommendation and guidelines) (WP7).
- In parallel, the analytic and numerical models to elaborate the risk assessment will be elaborated and validated by means of experimental analysis and deduction of empiric relations between the monitoring results, the performance on use and the conservation states (WP8);
- Elaboration of expert tools for: residual life and residual risk evaluation - maintenance strategy - cost & time analysis, for the construction of the final Decision Supporting Tool (DST) for the diagnosis and the scheduled maintenance of a Monument as a Whole (WP9). This will be integrated and complete the MACH Platform.
- Elaboration of an exploitation plan for the diffusion and dissemination of MACH results (WP10).

The main objective of the project is the jointly development of a Decision Supporting Tool (DST) (WP9 - starting time - T_{0+30} final model T_{0+48}) based on a model elaborated from data derived by the monitoring of the weathering rate of selected monuments considered as a whole and integrated in their environmental context and by the evaluation of the effects of climate on external and internal materials (stone, brick, mortar, timber, metal, wall paintings).

The pivot of the project is the breakthrough web driven interactive MACH Platform (**MaP**) to which definition and implementation all partners will contribute (**WP4**/**Task 4.2** - starting time T_{0+1}, beta version T_{0+12}, final version T_{0+47}) and whose operative structure will be built by TUC and ICVBC and managed by the server of TUC. This represents the virtual world that will contain all the real data coming both from architectonical, stylistic, historical documents and from the diagnostic and monitoring investigations. The first step (**WP4**/**Task 4.1** - T_{0+1} - T_{0+3}) is the definition and development of a common data interchange format language (from general discussion at the Kick-off meeting) for collecting-filtering and elaborating data coming from different sources (digital, analogical, electrical, optical) and this will be achieved either from the work done for representing and documenting the monumental benchmark sites (WP2/Task 2.1) and from the critical examination of literature concerning the evaluation of diagnostic and monitoring procedures (**WP3/Task 3.1 -** T_{0+1} - T_{0+3}). An essential part of the platform will be the interactive virtual 3D model of monumental test sites (WP2/Task 2.2). This will contain active point correspondent to the effective sensors localization, whose filtered data can be visualized in real time (4D model).

On the basis of a preliminary monuments list, suggested by the partners, the project intend to assume as primary common case study some historical buildings in the old city centre of Ortigia, Siracusa (UNROMA1): the Borbonic Jail with the Graziella Quarter whose archetype is of Roman origin. Other historical buildings will be adopted as collateral monumental benchmark sites:
- Tower of the cathedral of Porto (Porto)." - UMINHO
- Saint Jacob, (Luven, Belgium) - KUL
- Saint John Church (Gdansk, Poland) - IPPT

Each of them is characterised by different construction techniques, different environmental contexts, and specific conservation and/or restoration practices. These are under restoration and some structural and environmental parameters are under control, since several years, by suggesting partners.

In the **WP2** an initial guideline to identify the monuments from a stylistic and constructive point of view will elaborate (**Task 2.1** T_{0+1} - T_{0+3} - general discussion at the Kick-off meeting) and the different sites will be documented as a whole. In parallel 3D GIS virtual images will be derived (**Task 2.2** - T_{0+4} - T_{0+15}) by the use of geodetic and topographic tools (digital photogrammetry, 3D scanners etc). These will be used for precise data storage (diagnostics, monitoring, interventions, weathering etc.). A new tool will be developed for support the interactive construction of the 4D dynamic representation to help the user to connect (geo-referenced) the different types of time-dependent monitored data on the 3D model of the selected historical building (**Task 2.2** - T_{0+18} - T_{0+19}). The interactive geometrical 3D model will be used in WP8 (**Task 8.1**) T_{0+12} - T_{0+47}) for the distinct element analysis of the selected monuments, (a pre-processor will be developed to insert the geometrical 3D-model into the discrete 3D-model (**Task 2.2** - T_{0+30} - T_{0+31}).
The **WP5** contains the innovative aspects of the project the development of a Wireless Sensor Network and the improvement of a Fiber Optic Sensor (**Task 5.1** - T_{0+1} - T_{0+12}) system for stationary monitoring of structural and environmental parameters and of portable diagnostic tools or technologies (**Task 5.2** - T_{0+1} - T_{0+12}) for on site damage evaluation. Some of them will be new and others will be derived from the exploitation and implementation of the outcomes of past EC funded research projects (**WP3 Task 3.2** - T_{0+1} - T_{0+3}). In fact, the MDDS prototype derived from the COMPASS project could serve very well as a common preliminary starting point as *low cost diagnostic tool* for *visual inspection*, with a sound and consequent description and assessment of the state of conservation of all cases. This will be implemented and improved during the project at the end of which it will be merged in the web driven interactive MACH platform.
In **WP6** will be discussed and defined (first project workshop PW - T_{0+9}) the most meaningful parameters to be monitored and the technologies (device and methods) to measure them (**Task 6.1** - T_{0+10} - T_{0+13}). The new developed devices and other on the market technologies will be applied on the common monumental test site of

Ortigia (UNROMA1). A very Recent Fiber Optic Sensor integrated (FOS) system (SMARTEC) for stationary structural monitoring. (**Task 6.2** - T_{0+13} - T_{0+43}) will be mounted at the Borbonic jail for compare the structural data with those obtained using the new WNS. At the Saint Jacob church (KUL - Leuven) will be placed a dedicated FOS system, mounted in the main nave, for comparison with the existing structural systems for monitoring the different structural behavior as a function of environmental actions. At Saint John Church (IPPT - Gdansk) the FOS will be installed to investigate the in situ characteristics of the hydration progress period for the lateral internal walls using Fiber Bragg Grating sensors. The WSN once developed and checked on a monument in Florence T_{0+14} (ICVBC) will be mounted at Ortigia and at the tower of the cathedral of Porto (UMINHO). In the first case the structural sensors will be validated in parallel against the FOS system placed at the Borbonic jail, while in the second one it will be validated with the existing standard cabled sensors system. The portable diagnostic tools (new and olds) will be used, at Ortigia, for monitoring some time or environmental dependent parameters (**Task 6.3** - T_{0+13} - T_{0+43}).

To describe a behaviour of the whole construction in a way allowing to model Risk Assessment and estimate Residual Life (WP8 and WP9) special care must be taken to monitor all the deterioration driving factors generated by the environment. For this purpose necessary determinations (**Task 6.3** - T_{0+13} - T_{0+41}) of mechanical properties of structural materials, moisture, salt, aggressive gases, particulate inorganic pollutants and biodeteriogens existing in the structural and decorative elements (external and internal) will be done accompanied by environmental loads estimation (wind, temperature, solar irradiance, rain impact, water table, seismicity and para-seismic vibrations etc.). The complete panoply of these measurements will be done at the common monumental test site (Ortigia), while in related benchmark sites only some of them will be made after a deeper analysis of prevailing environmental factors. Extensive monitoring campaign will be performed at 3 time steps ($T_{0+ 17}$ – T_{0+29} - T_{0+41}), being the first and the last scheduled in conjunction with the 3rd and 4th PWs respectively. The influence of seasonality (**Task 6.4**) will be verified on some parameters at Ortigia for 4 time steps (T_{0+17} - T_{0+25} - T_{0+34} - T_{0+42}) corresponding at the one of the (hopefully) different seasons (spring – summer – autumn – winter).

In the **WP7,** once examined and discussed (at the 5th PW - T_{0+41}) the data elaboration coming from the monitoring campaigns and the stationary WSN and FOS systems, will be established what reliable new technologies (**Task 7.1** - T_{0+41} - T_{0+44}) and new methodologies (**Task 7.2** - T_{0+41} - T_{0+44}) will be normalised and suggested as recommendation for the aim to quantify exactly the parameters needed for establish the risk assessment of a monument as a whole.

The **WP8** has the key responsibility to elaborate the analytical and numerical simulating tools (STs) for analysis, diagnosis, safety and risk assessment for the best design of the intervention (maintenance) method of a monument (**Task 8.1** - T_{0+12} - T_{0+47}), these STs will be based on the Finite Element Method (FEM), Finite Differences Method (FDM), Boundary Element Method (BEM), Distinct Element Method (DEM). Before going into depth on numerical models, attention will be paid to the formulation and application of simpler analytical methods (**Subtask 8.1**.**1**- T_{0+12} - T_{0+47}**)**. It will not always (certainly not for all monuments) be possible to include complex and expensive analysis tools – which is the reason for which low-cost universal wireless network sensors are designed for in WP5. These methods are of prior importance since these can provide a close relation with the structural behavior of the monument as a whole and the information obtained from monitoring campaigns.
In this WP the 3D model (quantitative-visualization tool realized in WP2) containing all the structural and non-structural key elements affecting the conservation of the monument and calibrated with in situ monitoring measurements (made in WP6) will be used for an innovative structural analysis of the selected masonry monument (**SubTask 8.1.2** - T0+44 - T0+47). The selected monuments will be analysed via the available numerical codes (among which the finite element code NOSA developed by the Mechanics of Materials and Structures Laboratory of ISTI for (i) static analysis, (ii) collapse analysis, and (iiii) modelling of strengthening operations).
The results will be used for the prediction of short, medium and long-term behavior of the monumental structure and the materials investigated (at all scales) for the application of the best maintenance or protection strategy.

In **Task 8.2** (T_{0+12} - T_{0+47}) will be elaborated and validated the Probabilistic Risk Assessment Model through the definition of the parameters to be mapped in the numerical model (**Subtask 8.2.1 -** T_{0+27} - T_{0+30}) and the identification of the Constitutive Laws (material behavior) for the different materials and elements (**Subtask 8.2.2 -** T_{0+27} - T_{0+30}).
All numerical simulating tools will be integrated into the MACH Platform (WP4) and will be used later in WP9 for the elaborate the final expert Decision Support Tool (DST).

In the **WP9** the Decision Supporting Tool (DST), after the integration of all kind of information gathered in previous WPs and using the STs elaborated in WP8 will be developed (T_{0+30} - T_{0+48}). It will provide an expert system for a prognosis on the evolution of damage, residual life, safety and residual risks in the medium and long term based on the comprehension of the physical processes that can affect the conservation of a monument as a whole. In turn the DST will permit the identification of repair, strengthening and maintenance needs to allow a preventive conservation (scheduled maintenance) to be developed according to time and cost requirements.
The DST will lay on the European web driven MACH platform and will be made accessible in the future to possible end-users (public and private) in the field of conservation of the European Monumental Heritage. The DST will synthesise all the experience and concepts yield by the project *(Damage Assessment, Intelligent Monitoring, Simulation and Risk Analysis - DAMSRA)* and will thus promote (and sustain) conservation programmes based on the comprehension of decay/damage processes of a "Monument as a Whole". The essential module of the DST will consist of a digital guideline involving the following sections: (1) assessment and documentation of the state (of conservation) of the monument as a whole; (2) analysis and diagnosis of decay phenomena; (3) Risk analysis (including environmental influences); (4) Intervention; (5) Maintenance planning. The module will start from the existing MDDS prototype created within the EU project COMPASS, developing the damage diagnostic system to a complete tool within the DAMSRA concept with an enormous step forward. The DST will be not just a mathematical algorithm which can find or fail to detect a solution, but a system integrating experience and data coming from the previous WP's for a specific monumental case investigated as a whole. The DST will not automatically carry out diagnosis and risk analysis, based on "all purpose" unrealistic algorithms, but it will provide the "best possible support" (assist decision taking) on the way diagnosis must be carried out (by providing support on possible involved physical processes, important parameters to be taken into account, specific non-destructive tests and monitoring programme for the given risky problems) and the same for risk assessment (how to formulate it depending on the nature of the problems and the available information).

AT the kick-off meeting (T_{0+1}) a preliminary exploitation plan (**WP 10**) will be drafted identifying the possible target groups (restorers, architects, researchers, engineers, owners of monuments, politicians, decision makers) and the possible end users to insert as *MACH mirror-group* At the mid term meeting (T_{0+24}) the preliminary draft will be implemented and the possible exploitable results will be indicated. The exploitation plan will be updated at T_{0+37} and T_{0+47}. The new methods for diagnosis/monitoring have the potential to be developed into commercial products, which can be established at the market by SMEs.

Risk involved and countermeasures

Risk related to the capacity and purposefulness of the DST
The development of the activities included in WP9, and particularly the DST, involves a number of risks regarding its purposefulness, information processing capacity and the adequacy of the resulting support regarding conservation principles.
The DST, as an expert system able to support decisions covering the different aspects encompassed by the study and conservation of a historical structure, is aimed at significant generality regarding the variables of the problem (construction typologies, state of conservation, chemical, biological or physical decaying processes, and so on). Given the large variety of possible structural situations and problems, there could be some risk of producing a DST only able to support a too limited variety of situations or problems. Two measures are envisaged to counteract this risk. First, the DST will be developed taking the selected monuments as benchmark

or reference cases. The capacity of the DST to handle the problems and situations represented by the set of selected monuments will be constantly assessed throughout its development and validation. These case studies have been chosen so that they actually represent significant problems or deteriorating processes found in real buildings. Hence, the DST will be able to handle, at least, variety of problems frequently encountered in both masonry and timber structures. Second, the DST will be provided with a general structure allowing gradual or further development or enrichment with additional structural types, damage processes or general situations, so that its possible limitations (in terms of variety of structural cases or deterioration phenomena) may be overcome by enriching it with new information according to previously defined protocols. It must be recognized, however, that an absolutely universal tool dealing at once with all kind of problems does not constitute a realistic aim.

Adequacy of solutions and compliance with conservation needs and principles.

The DST is aimed, in particular, at supporting decisions related to intervention (including repair or strengthening) and maintenance. The DST will be designed to provide technically efficient solutions adequately linked to the diagnosis on the causes of structural damage or material decay. However, technical efficiency is not a sufficient condition as the solutions are also to be satisfactory and even optimal from a conservation point of view. In other words, the proposed strategies or interventions should comply with conservation principles oriented to minimize the possible impact on the original materials and structures and to disregard (or minimize) possible cultural losses. (Conditions such as minimal intervention, chemical and physical compatibility, reversibility, non-invasiveness and controllability are among those that should be considered and balanced while deciding about possible operations). To prevent from the risk of solutions not fully aligned with conservation principles, the DST will operate with intervention technologies or strategies carefully chosen to fulfill them. Furthermore, criteria resulting from conservation principles will be embedded in the DST and will influence on the operational system to produce solutions combining technical efficiency and conservation philosophy to optimal extent.

Capacity to manage and process information

The DST is intended to gather and integrate information resulting throughout the set of activities involved in the study and conservation of a monument, including documentation, inspection, monitoring, structural analysis, diagnosis and the design of interventions or maintenance operations. The information gathered through all these phases should be stored in the MaP in a systematic way so that it can be automatically acquired by the DST. The DST should be also provided with a collection of selected strategies, methods and options (regarding inspection, monitoring, and maintenance) appropriate for a variety of different situations. The DST should be able to "compare" the information available on the building (and the results already available on it), with the collection of strategies and solutions and then, using both qualitative and quantitative in-built selection algorithms, to conclude on the "best one", which is provided to the consideration of the user. There is some risk of unsatisfactory capacity to handle and integrate this information (which is of very different nature) and to process it using both qualitative and quantitative operations. In part, these difficulties are to be overcome again by taking the selected monuments as reference cases to be considered to assess the adequate functioning of the computational tool throughout the entire process leading to its development. The possibility of developing an efficient tool is also granted by the previous experience of some of the partners in handling related systems (in particular, of TNO in developing the existing MDDS – Monument Damage Diagnostic System).

Nevertheless, the experiences in this field of the institutes involved, and the advanced equipment available, allow to expect a real step forward. In fact, the chance of a sound final deliverable is considered high. This expectation is based upon the experience of the involved institutes in both research in the field of damage assessment / diagnosis, in the field of development and application of non destructive and low invasive techniques and finally in knowledge transfer, making use of expert systems. A guarantee for practical applicability is to be found in the presence in this project of end-user organizations (like Monumentenwacht and Transilvania Trust) and other important supporting external Institutions.

Time lapse for monitoring

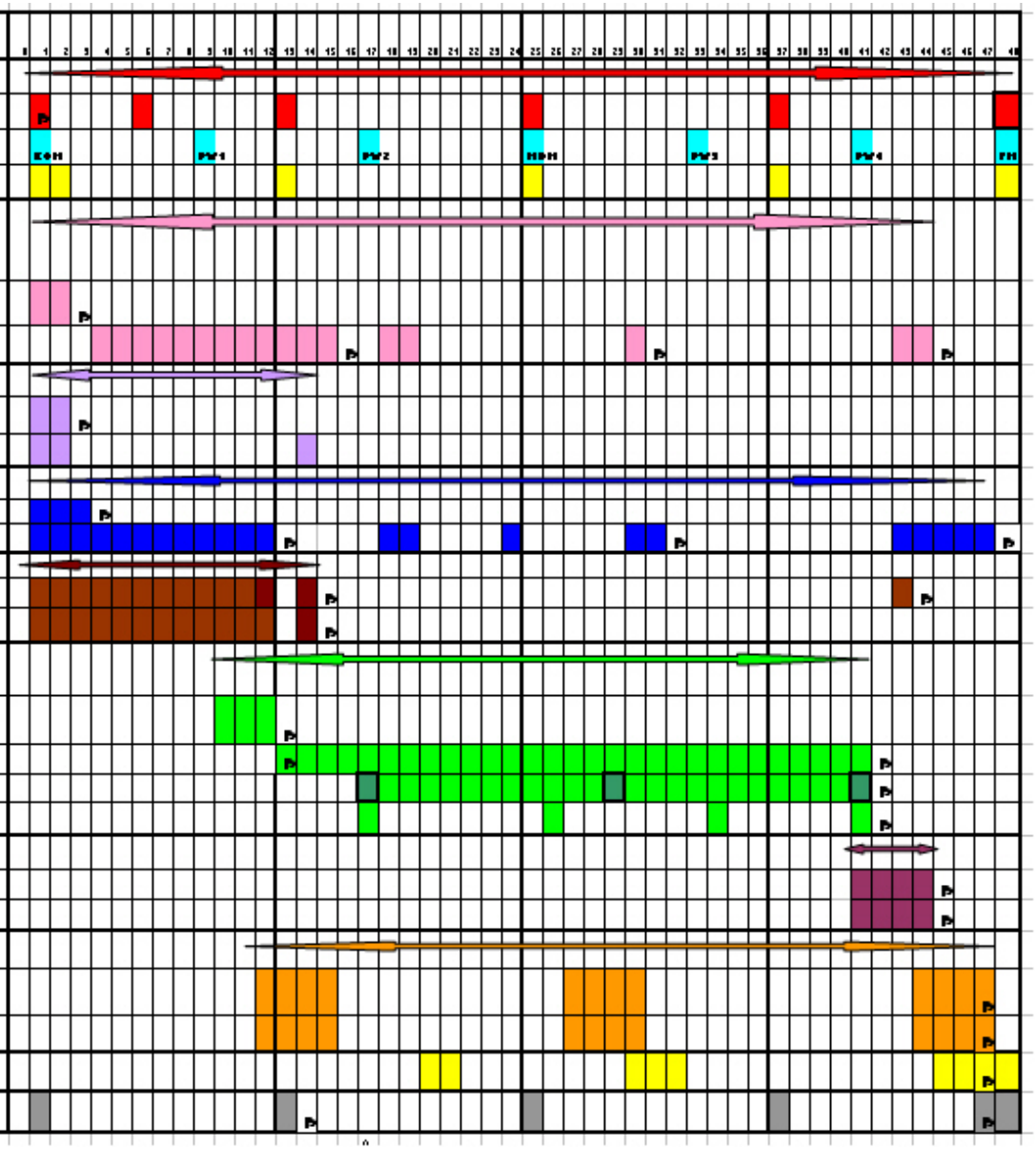
In fact, due to time constraint the choice of the period of about 3 years, into the 4 years of duration for RTD activities, for the monitoring programme of the monumental benchmark sites (with 3 time steps at about 1 year interval and 4 time steps for check the seasonality of some parameters) could be not fully adequate for evidence the parameters trends in time (changes are too little to be evidenced and measured, by the WSN, FOS and

portable diagnostic tools). This fact could hinder the effective determination of the "on site damage" and consequently its trend (during monitoring) to validate the analytical and numerical Simulating Tools. To overcome this drawback the monumental benchmark site have been selected taking into account that most of the "structural risk parameters" are under monitoring since several years and these data will be used to validate the new diagnostic tools and to improve the simulating tools. Other possible countermeasures could be to enhance the sensitivity of the diagnostic tools and sensors or to prolong the monitoring duration for another year.

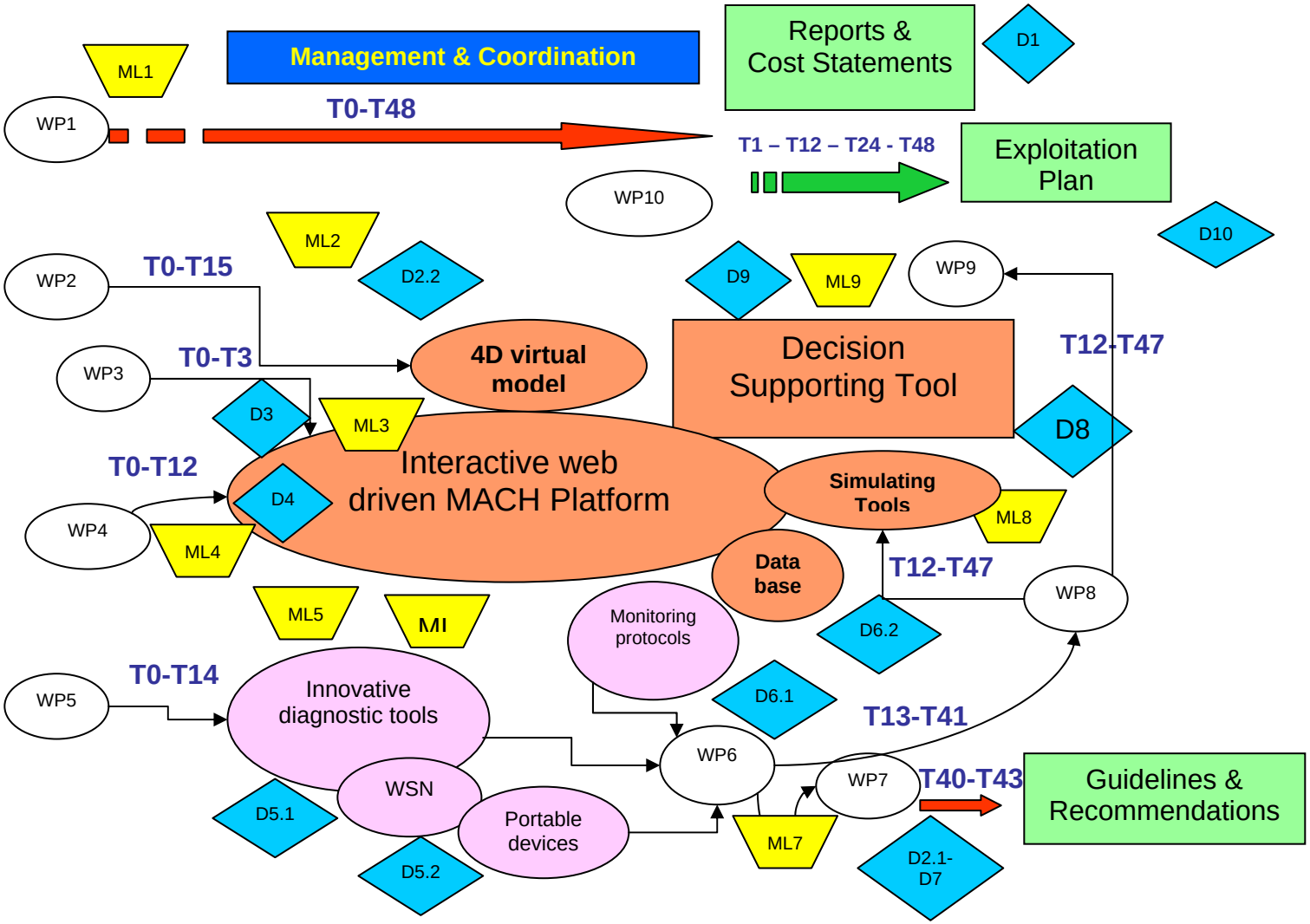
In the following chart and diagrams are reported the :

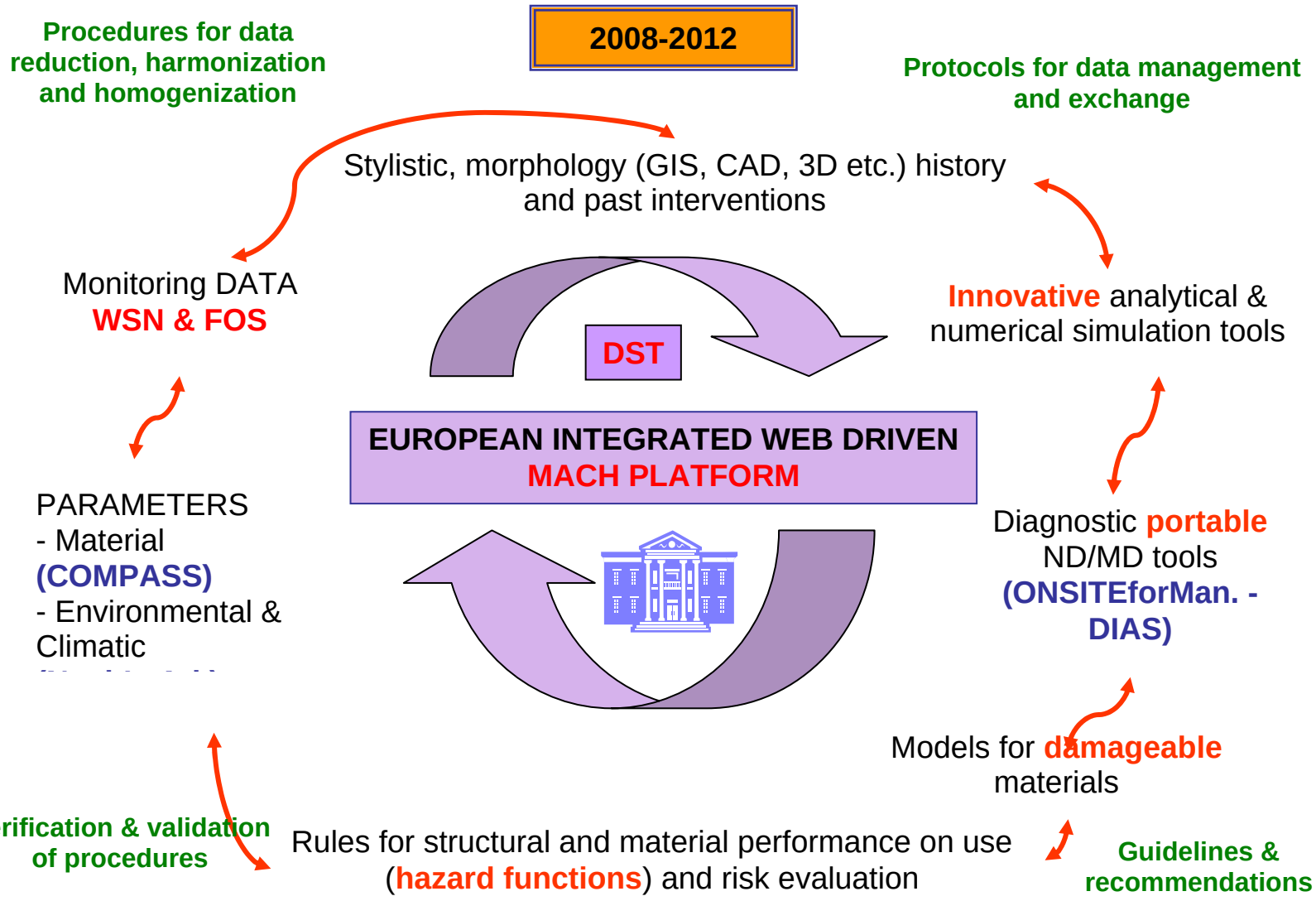
- MACH Gantt (pag 12)
- MACH Pert (pag 13)
- MACH Platform (pag 14)

WP	Tasks	MACH GANTT
1		**Management and administration**
	1.1	Coordination and reporting
	1.2	Meetings and workshops
	1.3	Administration and funding
2		**Interpretation and characterisation of a construction of the Cultural Heritage "as a whole"**
	2.1	Description of the common monumental test site and related benchmarks
	2.2	Construction of the geometrical interactive 3D-models
3		**Monitoring and diagnostic procedures**
	3.1	Reflection on the concepts of Analysis and Intervention (SOTA)
	3.2	Exploitation of past EC funded projects
4		**MACH Platform**
	4.1	Data format establishment.
	4.2	Development and built of the platform
5		**Innovative diagnostic tools**
	5.1	Wireless Sensor Networks System
	5.2	On site Damage evaluation
6		**Monitoring of a Construction of the Cultural Heritage "as a whole"**
	6.1	Deterioration phenomena and processes: Selection of parameters, methods and protocols definitions.
	6.2	Structural diagnostic including the foundations
	6.3	No-structural diagnostic and materials decay
	6.4	Value of seasonality for on site monitoring determination.
7		**Standardisation of Techniques and Methods**
	7.1	New technology
	7.2	New processes, (Methodology)
8		**Analytical Methods: (probabilistic) Risk Assessment**
	8.1	Deduction of the monument state by means of analyticall methods and numerical tools
	8.2	Creation of a Risk Assessment Model
9		**Decision Supporting Tools**
10		**Dissemination and exploitation**



MACH PERT


Management & Coordination
ML1
WP1
T0-T48
Reports & Cost Statements
D1
T1 – T12 – T24 - T48
Exploitation Plan
WP10
D10
ML2
WP2
T0-T15
D2.2
D9
ML9
WP9
T0-T3
WP3
4D virtual model
Decision Supporting Tool
T12-T47
D3
ML3
D8
T0-T12
Interactive web driven MACH Platform
D4
Simulating Tools
WP4
ML4
ML8
Data base
T12-T47
WP8
ML5
MI
Monitoring protocols
D6.2
T0-T14
WP5
Innovative diagnostic tools
D6.1
T13-T41
WP6
WP7
T40-T43
Guidelines & Recommendations
WSN
D5.1
Portable devices
ML7
D2.1-D7
D5.2


2008-2012
Procedures for data reduction, harmonization and homogenization
Protocols for data management and exchange
Stylistic, morphology (GIS, CAD, 3D etc.) history and past interventions
Monitoring DATA
WSN & FOS
Innovative analytical & numerical simulation tools
DST
EUROPEAN INTEGRATED WEB DRIVEN
MACH PLATFORM
PARAMETERS
- Material
(COMPASS)
- Environmental & Climatic
Diagnostic portable ND/MD tools
(ONSITEforMan. - DIAS)
Models for damageable materials
Verification & validation of procedures
Rules for structural and material performance on use (hazard functions) and risk evaluation
Guidelines & recommendations

Note:
1 A work package is a major subdivision of the proposed project with a verifiable endpoint normally a deliverable or a milestone in the overall project.

The number of work packages used must be appropriate to the complexity of the work and the overall value of the proposed project. The planning should be sufficiently detailed to justify the proposed effort and allow progress monitoring by the Commission.
Any significant risks should be identified, and contingency plans described.
(Maximum length for the whole of Section 1 – 20 pages, plus the tables)

Table 1.3 a: Work package list

Work-package No	Workpackage title	Lead contractor No	Person-months	Start month	End month	Deliverable No
WP1	**Management and administration**					
	Task 1.2 – Meetings and workshops *Task 1.3* – Administration and funding	**P1** **ALL** **P1**	**3** **15** **2**	**T_1** **T_1** **T_1**	**T_{0+48}** **T_{0+48}** **T_{0+48}**	**D1.R** **D1.C**
WP2	**Interpretation and characterisation of a construction of the Cultural Heritage "as a whole"**					
	Task 2.1 - Description of the common monumental test site and related benchmarks sites *Task 2.2* - Construction of the geometrical interactive 4D-models	**10** **5**	**12.5** **29.5**	**T_1** **T_{0+4}**	**T_{0+2}** **T_{0+44}**	**D2.1** **D2.2** **D2.3**
WP3	**Monitoring and diagnostic procedures**					
	Task 3.1 - Reflection on the concepts of Analysis and Intervention (SOTA) *Task 3.2* – Exploitation of past EC funded projects.	**10** **8**	**8** **4.5**	**T_1** **T_1**	**T_{0+2}** **T_{0+2}**	**D3**
WP4	**MACH Platform**					
	Task 4.1 **–** Data format establishment. *Task 4.2* - Development and built of the platform	**14** **2**	**11** **16.5**	**T_1** **T_1**	**T_3** **T_{47}**	**D4**
WP5	**Innovative diagnostic tools**					
	Task 5.1 - Wireless Sensor Networks System *Task 5.2* – On site Damage evaluation	**8** **10**	**18** **48.5**	**T_1** **T_1**	**T_{14}** **T_{14}**	**D5.1** **D5.1.1** **D5.2.1** **D5.2.2** **D.5.2.3** **D5.2.4** **D5.2.5** **D5.2.6** **D5.2.7**
WP6	**Monitoring of a Construction of the Cultural Heritage "as a whole"**					
	Task 6.1 - Deterioration phenomena and processes: Selection of parameters, methods and protocols definitions. *Task 6.2* - Structural diagnostic including the Foundations *Task 6.3* - No-structural diagnostic and materials decay *Task 6.4* - Value of seasonality for on site monitoring determination and environmental impact.	**15** **10** **7** **5**	**11** **21** **28** **5**	**T_{10}** **T_{13}** **T_{13}** **T_{17}**	**T_{12}** **T_{41}** **T_{41}** **T_{41}**	**D6.1** **D6.2** **D6.3**

WP7	**Standardisation of Techniques and Methods**					
	Task 7.1 - New technology *Task 7.2* - New processes, (Methodology)	**8** **8**	**7** **6**	**T_{41}** **T_{41}**	**T_{44}** **T_{44}**	**D7**
WP8	**Analytical and numerical methods: Probabilistic Risk Assessment**					
	Task 8.1 – Deduction of the monument state by means of analytical methods and numerical tools.. *Task 8.2* – Creation of a Risk Assessment Model.	**10** **7**	**33** **19.5**	**T_{12}** **T_{12}**	**T_{47}** **T_{47}**	**D8.1** **D8.2** **D8.3**
WP9	**Comprehension of a Monument as a Whole: joint application and DST validation**	**15**	**38.5**	**T_{30}**	**T_{48}**	**D9**
WP10	**Dissemination and exploitation**	**15**	**19**	**T_1**	**T_{48}**	**D10.E** **D10.P** **D10.W** **D10.T** **D10.SW**
	TOTAL		**347.5**			

1 Workpackage number: WP 1 – WP n.

2 Please indicate oneactivity per work package:
RTD = Research and technological development (including any activities to prepare for the dissemination and/or exploitation of project results, and coordination activities); DEM = Demonstration; MGT = Management of the consortium; OTHER = Other specific activities, if applicable in this call.

3 Number of the participant leading the work in this work package.

4 The total number of person-months allocated to each work package.

5 Measured in months from the project start date (month 1).

Table 1.3 b: Deliverables List

Deliverable No	Deliverable name	Wp N°	Nature	Dissemination level	Delivery date
D1, **D1.R6,** **D1.R12,** **D1.R24,** **D1.R36,** **D1.R48**	REPORTS	**1**	R	PP	M1, M6, M12, M24, M36, M48
D1. C12, **D1. C24,** **D1. C36,** **D1. C48**	COST STATEMENTS	**1**	**O**	**CO**	M12, M24, M36, M48
D2.1 **D2.2** **D2.3**	- Guidelines for document and interpreting a monument as a whole - Database of construction and material characterisation of architectural heritage for 3D GIS - Interactive 4D virtual geometrical model.	**2** **2** **2**	O O O	PP PP PP	M3 M3 M15-M44
D3	Structured Data Base on recommended monitoring and diagnostic procedures related to decay and damage processes	**3**	R	PU	M3
D4	Web driven Interactive MACH Platform	**4**	O	PP	M12 M24
D5.1 **D5.1.1**	-Open wireless monitoring system - On site vibration monitoring device	**5** **5**	P P	PP PP	M12 M12
D5.2. **D5.2.1** **D5.2.2** **D5.2.3** **D5.2.4** **D5.2.5** **D5.2.6** **D5.2.7**	Portable diagnostic system for masonry damage evaluation HD - Hole drilling DR - Drilling Resistance CoDiT Surface meter Active Tomography Optimized on site NTD extraction methodologies for the evaluation of surface chemical deposits NTD Methodologies to estimate biodeteriogens on masonry surfaces.	**5**	P	PP	 M12 M12 M12 M12 M12 M12 M12
D6.1 **D6.2** **D6.3**	Monitoring Protocols Data Base Seasonality charts for environmental dependent parameters	**6** **6** **6**	O O O	PP PP PP	M12 M41 M41
D7	Guidelines and proposals of Standardizations for the validated techniques and methods	**7**	O	PP	M44

D8.1	Discrete Interactive 4D virtual monument model	**8**	O	PP	M47
D8.2	Analytical and numerical simulation tools	**8**	O	PP	M47
D8.3	Probabilistic Risk Assessment tool	**8**	O	PP	M47
D9	Decision supporting Tools (DST) for monuments conservation	**9**	O	PU	M48
D10.E	Exploitation plan	**10**	O	PP	M1-12–24-36-48
D10.W	Web site	**10**	O	PP- PU	M4
D10.P	Publications	**10**	O	PU	M36- 48
D10.SW1	Seminars and Workshops	**10**	O	PU	M25
D10.SW2		**10**	O	PU	M41
D10.T	Training Courses				M46

1 Deliverable numbers in order of delivery dates. Please use the numbering convention <WP number>.<number of deliverable within that WP>. For example, deliverable 4.2 would be the second deliverable from work package 4.
2 Please indicate the nature of the deliverable using one of the following codes:
R = Report, **P** = Prototype, **D** = Demonstrator, **O** = Other
3 Please indicate the dissemination level using one of the following codes:
PU = Public
PP = Restricted to other programme participants (including the Commission Services).
RE = Restricted to a group specified by the consortium (including the Commission Services).
CO = Confidential, only for members of the consortium (including the Commission Services).
4 Measured in months from the project start date (month 1).

Table 1.3 c: Work package description

Workpackage number	**1**	**Start date or starting event:**	**T1**
Workpackage title	**Management and administration**		
Activity type	**MGT**		
Participant n°	**ICVBC**		
Person-months per participant	**5**		
Activity type	**RTD**		
Participant n°	**ALL**		
Person-months per participant	**1 m/m for each partner for participate at the Meetings and Workshops (total 15 m/m)**		

Objectives

The main objectives are the management of the project, the coordination of partners' activities, organization of periodical workshops and the contact with the EC.

Description of work

Task 1.1 – Coordination and reporting

The philosophy governing this project is to ensure fruitful and continuous relationships among the member and to optimise the time and resources needed to achieve the objectives. Frequent communication and contact among partners will be maintained to enhance the collaboration and to verify the milestones and assess the progress of the work and transfer of techniques and results. Interim reports will be prepared in collaboration with all partners and a mid-term assessment will be submitted before the end of the 26th month from the date of the commencement.
Partners involved :ICVBC

Task 1.2 – Meetings and workshops

Periodical meeting and workshops will be scheduled in order to provide a forum for technical discussions, transfer of results within partnership and the elaboration of reports.
Partners involved : ALL

Task 1.3 – Administration and funding

The management of the project will ensure that the budgets established in the contract are followed and will ensure a rapid allocation of funds to the partnership.

Partners involved: ICVBC

Deliverables

D1.**R-** Interim reports (T_6)– - Mid term report (T_{24}) - Yearly reports at T_{12}, T_{36} - Final report (T_{48}).

D1.C – Cost statements after each year of activity $T_{12 - 24 - 36 - 48}$

Workpackage number	**2**	**Start date or starting event:**			**T1**
Workpackage title	**Interpretation and characterisation of a construction of the Cultural Heritage "as a whole"**				
Activity type[1]	**RTD**				
Participant n°	**ICVBC**	**UPV/EHU**	**KUL**	**SMARTEC**	**UPC**	**UROMA1**
Person-months per participant	**7**	**1**	**11**	**0.5**	**1**	**4**
Participant n°	**ITAM**	**IPPT**	**TNO**	**UMIHO**	**TT**	**Total m/m**
Person-months per participant	**2.5**	**7**	**1**	**7**	**1**	**43**

Objectives

- Selection of the common monumental test sites, collect basic documentation and synthesis as bench mark for actual monitoring practices

- Construction of the geometrical 3D models of the monuments and enrichment with monitored data in time (4th dimension)

Description of work

Task 2.1 Description of the common monumental test site and related benchmarks. [13.5 mm]

A list of possible monumental test sites has been suggested, of which partners involved can guarantee access and authorization for their use in the project: St. Jacobs-Leuven (BE), Barcelona Cathedral (ES), St John Church – Gdansk (PL), Porto – Cathedral (PT), Lisbon – Jeronimus (PT), Veltrusy Castle (CZ), Bannfy Castle (RO), Duques of Bragança, Guimarães (PT), De Waag Building, Amsterdam (NL), Grazziella Quarter, Ortigia (IT).
A preliminary selection foresee the adoption of a common test area in which all the technologies and methodologies developed within the project will be applied, while only a selection of them will be addressed in other three monuments. The case studies include different types of buildings and different types of conservation problems. Each test case will have description of monumental test site; stylistic and constructive identification; history and past interventions, state of conservation of the monument and morphology identification.
Each synthesis will serve as bench marks for existing monitoring practices and will helps to identify the different dimensions of the monitoring problem.

In order to provide additional information a new methodology for a repetitive evaluation of a state of preservation of architectural heritage will be developed providing a guideline for collection of data. The data will be structured into a database and linked to the 3D model. The database will be designed for damage assessment and maintenance. The link with 3D GIS models will be done in collaboration by CNR-IST, KUL, UMINHO and IPPT. The development of the methodology of data collection, its organisation and presentation will be carried out together with the 3D GIS model developed. Optimised methodology for a repetitive evaluation of a state of preservation of architectural heritage will be validated and demonstrated on the testing site of the project. The following benchmarck monumental test sites have been identified for the project:

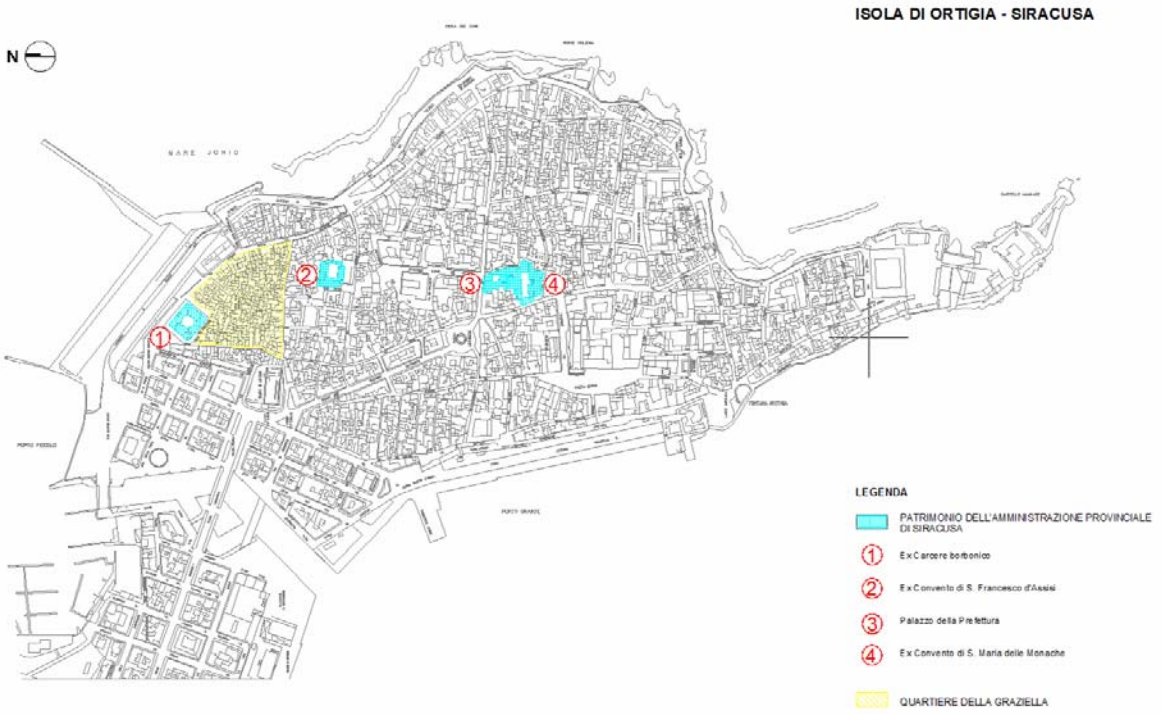
1 - Ortigia , Siracusa,(Italy)
2 - Church of Saint-James, Leuven (Be)
3 - Cathedral of Porto, (Portugal)
4 - St. John's church, Gdańsk (Poland)

1 - Common test site for DST validation, Ortigia, Sicily, Italy

The **Island of Ortigia**, a UNESCO world heritage monumental site, is the Old Town of Syracuse, in Sicily, resulting from a stratification of 2700 years of history over a space of land only one square kilometer. In the Old Town one will find archaeological sites filled with temples, castles, theaters, buildings, piazzas, old bridges, and original Baroque architecture. Originally established by Corinthian colonists in the 8th century BC, Ortigia has been home to Greeks, Romans, Arabs, and, more recently, Spaniards. Additionally, unlike many cities on the mainland, Syracuse was not destroyed and buried during the ages; so much of its original construction is visible today, though it was lacerated by the seismic events of the last centuries, started with the earthquake of 1542 until the last one in 1846.

The common test site for project has been selected in the Graziella quarter (shaded in the figure below), whose archetype is of Roman origin. In this quarter, seen as a whole monument, some objects are considered, as shown in the closer view below:
- its preeminent building, the Borbonic Jail (denoted by number 1),
- five typical old buildings for common housing. These buildings are "sensible" dwellings, meaning that they are both "vulnerable" and "meaningful representative portions of the city fabric".

The buildings are in masonry with timber beams and slabs (sometimes added steel beams can be found). Environmental problems are mainly related to the nearby sea that causes saline attacks to plaster and limestone bricks, along with the traffic pollution coming from the new town of Syracuse. Most of the problems that usually endanger monuments are to be found in Ortigia.



The Borbonic Jail is a single large masonry building in a large square. It was conceived under the Borbonic domination in Sicily by the architect Spagna, according to the "Panoptical" construction method, which consisted in building blocks radially placed around a center. The interesting aspect about this monument is that it is well embedded in a corner of the Graziella Quarter and constitutes a rip in its complex and multifaceted fabric.
In order to understand the portion of the city fabric under consideration as a whole, context relationship within the Graziella Quarter shall be studied on the basis of a knowledge-based "reading" of the fabric, with particular emphasis to the concepts of aggregation and juxtaposition. This study will take advantage of the geometry data recently acquired during an extensive survey of the quarter.

The Borbonic Jail, Ortigia, Siracusa

The following phase will be more technology-based, with the following activities:

a) The Monument will be 3D-scanned so that information from the database developed in WP4 shall be attached to its tridimensional representation. The 3D view shall also be used in developing the finite element model for structural and seismic analyses in WP8.
b) The Borbonic Jail shall be monitored with the purposely developed wireless sensors. Four of them shall be placed in four different zones in the Jail so to monitor mechanical quantities, such as stresses and crack widths in parallel with the FOS system. In the attic of the Jail, 3 additional wireless sensors shall be placed to monitor various environmental parameters, which also affect the adjacent quarter, such as: seismic-induced accelerations, pollution level, rain level. The attic of the Jail shall also be the place where the central acquisition unit receiving the data from the other sensors placed in the city fabric shall be located.
c) The selected dwellings (complete geometry surveys will be available) shall be monitored, through the innovative wireless instrumentations, for their local parameters: stresses and cracks (placed in a number of 4 per housing). The wireless sensors shall convey their data to a check point unit placed on the respective roof, from which they will be conveyed to the central acquisition unit placed on the Jail attic. Thanks to their representative nature, the results obtained from the five dwellings shall be extrapolated to other portions of the fabric, in order to obtain, in an efficient way, a comprehension of both the fabric and its architectural emergence (the Jail) as a whole.

The available and new information will be used for the development and illustration of the ST (WP(). During all the phases described above, the Regional Province of Syracuse shall be of full support.

2- Church of Saint-James, Leuven, Belgium

The construction of the western tower of the church of Saint James dates back from 1220. During several subsequent building phases, the Romanesque church has been replaced and extended by a church in early Gothic style. The wooden roofs in the central and side naves were replaced with masonry vaults, and flying buttresses were added. The structure itself is located on a former swamp, reclaimed by the monks at the time of construction. The load-bearing capacity of the subsoil is limited, causing large differential settlements. At several occasions in the past, restoration works took place. However, due to the excessive cracks observed, it was decided in 1963 to close the church for service, in fear of its structural collapse, to remove the severely cracked masonry vaults of the side naves and to shore up the pillars of the main nave. Additionally, in 2000, the remaining flying buttresses were removed and replaced by tie-rods.

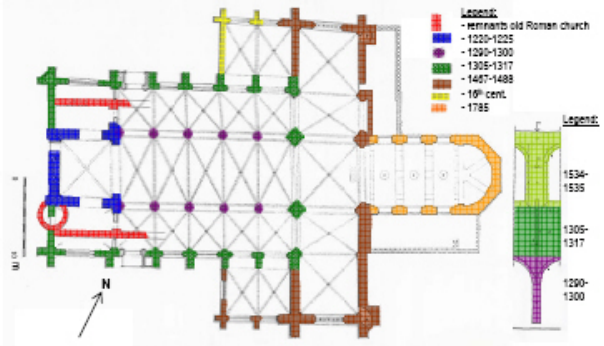
The history of this church already reveals several interesting items related to its structural problems:

- 1484-1485: construction of bell-tower (masonry and wood) on crossing. Dismantled in 1735 because of severe state of decay;
- 1485-1488: reconstruction of masonry vaults in side nave – northern and southern side;

- 1534-1535:
  - Construction of additional level with windows in main nave;
  - Construction of supports and abutments of flying buttresses;
  - Removal of wooden barrel vault;
  - Construction of masonry vault in main nave (arching: Gobertange stone)
- 1806: the pillars are strengthened with steel rings;
- 1905: request for consolidation and strengthening after local inspection and in view of severe cracking in the west wall of the northern transept (after painting in 1872)
- 1929 and 1936: the flying buttresses (those that remain) are in bad condition;
- 1950-1953: repair of war damage (roofing, windows and stucco-ceiling)
- 1956: main nave and two side naves are out of plumb for 30 cm. Two years later an increase with 10 cm is measured;
- 1963: the church is closed down;
- 1965-1971: phase 1 of restoration 1961-1974 (dismantling of vaults in side nave; shoring of main columns, shoring of side naves);
- 2000: dismantling of flying buttresses;
- 2005: consolidation measures: repair of roofing (leakage), renovation of sewer system.

Figures

Figure 1: Historical building phases



St. John Cathedral, Leuven - Flying buttresses and historical phases

In 1961, the collapse of the church was feared. To prevent further deterioration, it was decided to take immediate action. The plan consisted out of 3 subsequent phases, of which only preparatory phase one and phase 2 (partly) were executed. Until now the structure is supported, already during 40 years, by means of a temporarily shoring.
An extensive survey to collect required data took place since 1995. Also at this very moment, several parameters are monitored at discrete moments in time. Following information is collected:

- Geometry and structural layout;
- (differential) settlements
- Layout of foundation system and load-bearing capacity of subsoil
- Material properties of brick and stone masonry of several subsequent building phases

The objective of the City of Leuven (B) is the re-use of the building, with a large architectural freedom. In that the structure can serve as an outer shell, with a new infill that can be designed afterwards. Therefore, the load bearing capacity of the foundation will be consolidated using micro-piles.
In the framework of this project proposal, this case study will be incorporated as follows:

- Case study in the development of a 3D model of surveyed construction to attach and display

information coming from database developed in WP4 allowing for integration of time dependency of information (4th dimension). The available monitoring data will provide sufficient test data of various sources for this purpose.

- Case study in the development of the stationary optical sensors (FOS), to be installed in the attic of the church in longitudinal and transversal direction, to monitor the structural behavior of the church, before, during and after the foundation strengthening (WP6).
- Structural diagnosis including the influence of foundations and underground (WP6);
- Construction of 3D finite element model based on 3D geometrical information (WP8).
- Available and new monitoring data are used to feed probabilistic material models (masonry compressive strength). The latter allow for the illustration of the objective risk assessment methodology (WP8);
- The available and new information will be used for the development and illustration of the DST (WP9). This experience will be transferred to the general City of Ortigia case study. This in close collaboration with TNO and Monument Watch Nl and Monument Watch Flanders.

3 - Cathedral of Porto, Portugal

The cathedral of Porto is the selected Portuguese monumental test site used for the interpretation of a monument as a whole. The monument is located in the second city of Portugal, at the top of Douro River. The origin of the building is the middle of the 12th century. For 800 years, the settlement was a repository of added parts. From this state of a continuous construction yard, the main fabrics are: Romanesque and proto-gothic, gothic, renascence, mannerist, baroque, neoclassic. Contemporary works date from the first half of the 20th century.

The main problems detected in the cathedral deal with the stone deterioration of the façade; movements/foundations, problems in the chancel and visible cracking in the north and especially in south tower (see Figure). The damage was mostly visible in the tower which exhibit distributed cracking and significant out-of-plane movements. The existing damage resulted in the past addition of three iron ties (date unknown). It is also noted that the masonry walls in the vicinity of the anchorages are also deformed, as expected due to the application of a large point load. An integrated intervention was carried out in 2004 in order to strengthen and repair the major damages.

Porto cathedral - south view and main façade.

Given the cultural importance of the building and the significant damage in the South tower, a monitoring system based cable conventional sensors was planned and installed after the intervention. The system includes four waterproof crackmeters in the largest cracks, two strain gages for the new ties, two biaxial clinometers to measure the tilting of the tower, as well as temperature, humidity and wind sensors. The system includes a GSM interface for remote monitoring. Thus, this monumental test site will be mostly used for the validation of the monitoring program based on the innovative WNS by comparing its performance with the monitoring system already installed.

In the framework of this project proposal, this case study will be incorporated as follows:

- Case study in the development of a 3D model of surveyed construction based on spatial information. A 3D finite element model based on 3D geometrical information will be used for numerical analysis (WP8).
- Case study in the validation of the WNS and structural identification based on ambient vibration as well as structural damage assessment (WP6).
- Static and dynamic parameters derived from the WP6 will be also used as material data in numerical modeling (WP8)
- The available and new information will be used for the development and illustration of the DST (WP9).

4 - St. John's Church, Gdańsk, Poland

St John's church in Gdansk is situated in the north part of the Old Town in the vicinity of Motława River on the sand brought on swampy meadows. It is a brick masonry structure. Foundation of the church was made as spot and continuous stone footing.

It had been constructed over a hundred years in the two main periods:

- From around 1360 to the beginning of the XV century – construction of a 3 nave 18 m high church with a single nave presbytery and probably two chapels.
- Between years 1415- 1465 – rebuilding into the church with 3 nave presbytery, a transept and a tower.

About 15 years ago there was established "St. John's Cultural Centre" situated in the church and managed by Near Baltic Cultural Centre belonging to Gdańsk Municipality. Since that time restoration works have been continued to be able to host cultural events and holy services under one roof. The construction is checked by geodetic measurements and there are performed measurements of water table fluctuations and changes in chemical composition of ground waters. Archeological works are finished. IPPT has developed linear FEM 3D model of the construction. Under-floor channels to accommodate hydrostatic leveling network are built in presbytery and transept. IPPT is entitled to use the church as "a field laboratory".

The original church foundation had a depth of 2.2-3 m which was not enough on the marshland. First known problems arose in XVI century when differential subsidence of the pillars was observed and the foundation of 5 of them was stabilised. In the year 1679 eastern wall of the presbytery moved out of plumb towards the East for approx. 1 m. Also in 1689-93 and 1759-70 out of plumb movements and differential subsidence of the pillars were observed and their foundations were stabilised with timber piles and/or timber grates. Several other procedures were performed during the centuries with the last one being cement grouting of the foundation during the years 1996-97. The works did not stop the subsidence which increased due to earthquake under Baltic Sea in 2004. There are also old and new structural cracks – vertical and in vaults.

Subsidence monitoring system in east part of the church is considered a must to safely use the monument. Additionally crack opening should be monitored.

In the framework of this project proposal, this case study will be incorporated as follows:

- Laser scanning of the structure and 3D non-linear FEM modelling and analysis is planned.
- Correlation with Fiber Optics monitoring system (FOS) with hydrostatic leveling network based on unique FBG settlement and displacement sensors.
- Static and dynamic parameters derived from the WP6 will be also used as material data in numerical modeling (WP8)
- The available and new information will be used for the development and illustration of the DST (WP9).

Partners involved: KUL, SMARTEC, UPC, UNROMA1, ITAM, IPPT, TNO, UMINHO, TT

The Gandsk Cathedral, North Poland

Task 2.2 Construction of the geometrical interactive 4D-models [29.5 mm]

Different technologies for the construction of the 3D model of the monument considered will be evaluated and compared (laser-based 3D scanning, image-based modelling and stereo-matching, etc) to find the best solution for each given test case. Integration of different technologies on the same test case will also be possible.
The geometric data gathered (in most cases, 3D point clouds) will be processed in order to clean the data, transform them into a common 3D data format and make them usable in a web-based environment (data simplification and multi-resolution processing). Color mapping will also be applied (taking color from digital photographic acquisitions) when needed to enhance the data, producing a geometry and colour database.
The geometric data will be encoded in a data format that will allow to link any data coming from the monitoring devices to the corresponding geometric location and to take into account the fourth dimension (time step associated to each monitored value), in order to allow visualization of the evolution in time of the data mapped to the monument geometry.
3D data gathering will be performed by specific partners in parallel, working under a general agreement on the data formats and using common processing instruments.
This tool will support the interactive construction of the 4D dynamic representation, i.e. will help the user to connect the different types of time-varying monitored data and geo-reference them on the 3D model of the building. A user friendly interface will be developed to be able to attach and filter information in the database.
Partners involved: KUL, ICVBC, ITAM, IPPT, UMINHO.

SubTask 2.2.1 - Development of a database of construction and material characterisation of architectural heritage for 3D GIS models
The methodology for a repetitive evaluation of a state of preservation of architectural heritage provides a guide for the collection of data. The data has to be structured into a database and linked to a 3D GIS. The database structure will be developed by ITAM. It will be designed following the developed methodology but at the same time it will be an open instrument for data organisation on construction and material characterisation of architectural heritage for 3D GIS models. The specific reasons of the assessment like stylistic constructive identification, damage assessment, and maintenance will be subcategories in the database. The link with 3D GIS models will be done in collaboration of CNR-ISTI and KUL.
The data will be collected with respect to the purpose of the assessment i.e. stylistic constructive identification, damage assessment of façades, masonry, brick and timber (external and internal).

Optimised methodology for a repetitive evaluation of a state of preservation of architectural heritage will be validated and demonstrated on the common testing site of the project (Ortigia).

D. Koller, M. Turitzin, M. Levoy, M. Tarini, G. Croccia, P. Cignoni, R. Scopigno Protected Interactive 3D Graphics Via Remote Rendering *ACM Trans. on Graphics*, vol. 23(3), 2004, pp. 695-703.

G. Impoco, P. Cignoni, R. Scopigno "A six-degrees-of-freedom planning algorithm for the acquisition of complex surfaces ", International Journal of Shape Modeling, vol. 11(1), June 2005, pp. 1-23.

Paolo Pingi, Andrea Fasano, Paolo Cignoni, Claudio Montani, Roberto Scopigno, "Exploiting the scanning sequence for automatic registration of large sets of range maps", *Computer Graphics Forum*, NCC Blackwell, Vol. 24(3), 2005, pp.517-526.

M. Callieri, P. Cignoni, R. Scopigno, G. Gori, M. Risaliti "Beyond manual drafting: a restoration-oriented system", *Int. Jour. Cultural Heritage*, Elsevier., vol. 7(4), 2006, pp. (in press)

T. Franken, P. Cignoni, M. Dellepiane, F. Ganovelli, C. Montani, R. Scopigno, "Minimizing user intervention in registering 2D images to 3D models", The Visual Computer , Springer, vol. 21(8-10), 2005, pp.619-628.

M. Callieri, P. Debevec, J. Pair, R. Scopigno "A Realtime Immersive Application with Realistic Lighting: the Parthenon", Computer and Graphics, Elsevier, Vol. 30 (3), 2006, pp. 368--376.

Van Genechten B. and Neuckermans H., "Fusing laser scanning and photogrammetry creating close range architectural orthoimages", Augmented Heritage, proceedings of the 10th EuropIA international Conference, Sep 2005, p.35-44, ISBN 2-909285-32-4, Damascus, Syria, 13-15/09/2005;

Van Genechten B. and Neuckermans H., "Fusing laser derived DSM's and matched image edges to create close range ortho-images", Proceedings of the 11th International conference on Virtual Systems and multimedia (VSMM2005), Oct 2005, p. 473-480; Edited by: Hal Thwaites, ISBN 963 8046 63 5, Ghent, Belgium, 3-7/10/2005;

Milestones & Deliverables

ML2 – Synthesis of survey and documentation of selected cases studies: historical, geometrical – topographical data collection as bench marks existing monitoring practices; developing specification of data formats for 3D representation and mapping of monitored data,

D2.1 – Guidelines for document and interpreting a monument as a whole, based on synthesis.
D2.2 - Database of construction and material characterisation of architectural heritage for 3D GIS (integrated in the MaP).
D2.3 – Interactive 3D virtual geometrical model (first version regularly updated).

Workpackage number	**3**	**Start date or starting event:**					**T1**
Workpackage title	**Monitoring and diagnostic procedures**						
Activity type[1]	**RTD**						
Participant n°	ICVBC	UPV/ EHU	KUL	TUC	SINT	SMARTEC	INNOWEP	UPC
Person-months per participant	0.5	1.5	1	0.5	0.5	0.5	0.5	0.5
Participant n°	UN ROMA1	ITAM	IPPT	BAM	TNO	UMINHO	TT	**tot**
Person-months per participant	0.5	3	0.5	1	0.5	0.5	1	**12.5**

Objectives

- Critical evaluation of monitoring and diagnostic procedures
- Exploitation and implementation of the positive outcomes of the EC funded research projects in the field

Description of work

Task 3.1 Monitoring and diagnostic procedures with regards to the concepts of analyses and interventions - [8 mm]

When assessing a whole monument, its state of preservation, damage causes, structure, materials, environmental influences, etc. a number of assessment techniques have to be involved. Many problems and deterioration effects develops with time. Therefore, prior of the conservation and restoration interventions it is recommended to carry out an in depth assessment of diagnostic and monitoring procedures used in the same field. The methods are continuously developed and improved with the new technology advancements and can vary depending on the purpose of the investigations and the local factors involved. Application of non-destructive methods to historic structures and materials has recently undergone a great development, which consequently brought about a new possibility for improvement of the protection of cultural heritage. On the other hand 'traditional' diagnostic methods are still applied in a great scale. The conservators and architects together with other public or private institutions involved in the care and maintenance of monumental buildings have the need to take a decision based on optimization of the cost, destructiveness of the investigation and reliability of the diagnosis made.

The advanced investigation methods used for cultural heritage are often applications of methods invented and developed in other fields (e.g. thermography, ground penetrating radar, x-ray, sonic and ultrasonic testing and fibre optics). Their application for investigation of cultural heritage materials and structures requires further development and adaptations supported by a good understanding of their limitations for use on specific historic materials and constructions. For instance, the EC 5th FP project ONSITEFORMASONRY provided a number of improved methodologies for evaluation of historic masonry. However, based on the acquired knowledge in the project, further improvements can be suggested, for example - active thermography: quantification of depth of delaminations (influence of thickness of plaster and paintings), quantification of moisture content a the surface; microwave methods: calibration curves for the relationship between moisture content of materials and dielectric properties, influence of salt content, combination of different methods based on microwaves (radar, microwave borehole method, TDR).

This is a transversal Task in which all the partners are involved. They have long time experience with a great number of monitoring and diagnostic methods. An overview of the most diffuse methods, devices and procedures shall be structured in order to :

- Allow and unify their comparison (critical evaluation)
- Provide information that will be stored in the Data Base of the MACH platform

Preliminarily suggested categories listed in the overview are the following:

- Construction type – elements (masonry, render, plaster, foundation, timber frames, wall paintings, decorations, roofing, flooring, vaulting etc.).
- Material (stone, brick, wood, mortar).
- Damage and decay processes and their parameters (structural, physical, mechanical, chemical, biological, environmental).
- Purpose of assessment and time factors (preventive, damage assessment, long time monitoring, monitoring after conservation treatments, monitoring during construction works, early warning,

performance evaluation).
- Intervention scale (NDT, MDT and DT) and rate (rating of destructiveness):
- Costs, equipment and personnel requirements and practical operative constrains.

Partners involved: UPV/EHU, KUL, SMARTEC, UPC, UNROMA1, ITAM, IPPT, BAM, UMINHO, TT

Task 3.2 Exploitations and implementations of the outcomes (diagnostic and monitoring) of the EC R&D funded projects. - [4.5 mm]

Special attention will be paid to the exploitation of successful outcomes of the EC funded projects in the specific field of conservation Monumental Heritage.
The list of the relevant projects dealing with Cultural heritage is enclosed in ANNEX I. The partners in the Mach project have been involved in several EC and national funded projects. The development of new techniques and methods together with the know-how previously acquired by the partners participating in the projects will be the added value contributing to the successful of the project.
Some of the projects in which the partners have been involved in the past or actually ongoing and which have some outcomes relevant to the Mach project are listed below:

- Onsiteformasonry - On-site investigation techniques for the structural evaluation of historic masonry buildings (FP5 EC)**, BAM:** Guideline of the application of radar, active thermography and acoustic methods for the structural investigation of historic masonry, combination of radar and active thermography, damage catalogue. The innovation in the Mach project will be on the quantitative data, data fusion (direct super positioning of data from the same volume recorded with different methods).
- Sustainable Bridges (FP6 EC), **BAM:** Automatic scanner system for radar investigations and for testing of reinforcing laminates with active thermography.
- CHEF (FP6 EC**), BAM** and **ITAM:** Project, which has just been started (Kick Off Meeting in February 2007): CHEF Cultural Heritage Protection against Flood.
- Salt Control and Compass (FP5 EC), **TNO:** The knowledge acquired will be adopted and further developed in the framework of the MACH project. Theoretical models, investigation techniques, sampling procedures, analysis methodologies, expert systems developed in previous EC projects will be applied and improved.
- **ViHAP3D -** Virtual Heritage: 3D High Quality Acquisition and Presentation (FP5 EC), **ISTI CNR.** Design of improved software tools for the 3D digitalization of artefacts and architectures, oriented to provide more efficient management tools for the huge 3D models produced with 3D scanning technologies.
- **EPOCH -** a European Research Network on Excellence in Processing Open Cultural Heritage, (FP6 EC), **ISTI CNR:** Further evolution of software tools for supporting 3D scanning; the distribution of those tools to the CH community for wide dissemination and assessment; the design of new image-based methodologies for 3D models acquisition.
- **CULT STRAT -** Assessment of Air Pollution Effects on Cultural Heritage - Management Strategies (FP6 EC), **ITAM:** Maintenance and restoration costs, life cycles of materials and their treatments.
- **Noah's Ark –** Global Climate Change impact on built heritage and cultural Landscapes (FP6 EC) **ITAM:** Analysis of the wind flow around buildings and details. Experiments on scaled models including the pressure and wind velocity measurements which served primarily as the prototype for the subsequent numerical models used for parametric studies.
- **DIAS -** Integrated tool for in situ characterization of effectiveness and durability of conservation techniques in historical structures (FP5 EC), **TUC**, **SINT, ICVBC**: Portable, integrated device (DIAS) for in situ reliable and cost-effective characterization of the strength and stiffness of stones. Reference user-friendly database of in situ and in laboratory standard and non-standard (via DIAS) mechanical properties for a wide variety of stones and relevant software of the integrated DIAS instrument.
- ALA/95/23/2003/077-122 "Seismic Resistance of Cultural Heritage Buildings" [2004-2006], funded by the EU-India Economic Cross Cultural programme, **UPC**: Among the deliverables are a "Guidelines for the conservation of historical masonry structures in seismic areas" and a document on

"Identification of strengthening strategies".
- MCDUR - Effect of the weathering on stone materials: assessment of their mechanical durability (FP5 EC), **ICVBC**: **TUC, IPPT,** Use of portable instruments (Drilling Resistance Measurement System – Ultrasonic Pulse Velocity – Schmidt Hammer) for the evaluation of the stone durability on stone samples submitted to artificial and natural ageing.
- HISTOCLEAN Intelligent Surface measurement technology for laser cleaning of historic buildings and monuments (FP5 EC), **INNOWEP, ITAM.**
- MOMOREX – (CULTURE 2000 – CLT- CA12 2003) – **ICVBC**, European façades painted during the XVI century: Model of a project for the monitoring of deterioration subsequent to recent restoration.
-CHRAF (FP6 EC)**.** Priorities and strategies to support Cultural heritage Research Activities within ECTP and future FP7 activities (**UPV/EHU** subcontractor)

Partners involved: ICVBC, UPV/EHU, TUC, SINT, INNOWEP, ITAM, BAM, TNO

Milestone & Deliverables

ML3 – The state of the art of diagnostic and monitoring procedures of monumental buildings

D3 - Structured Data Base (to be integrated in the MACH Platform) on recommended monitoring and diagnostic procedures related to decay and damage processes, also including the innovations based on specific EC funded projects.

Workpackage number	**4**	**Start date or starting event:**				**T1**
Workpackage title	**MACH Platform**					
Activity type[1]	**RTD**				Total m/m	**17.5**
Participant n°	**ICVBC**	**UPV/ EHV**	**KUL**	**TUC**	**SINT**	**SMARTC**	**INNOWEP**
Person-months per participant	**5**	**2**	**0.5**	**3**	**0.5**	**1**	**0.5**
Participant n°	**UN ROMA1**	**ITAM**	**IPPT**	**BAM**	**TNO**	**UMINHO**	**TT**
Person-months per participant	**0.5**	**1**	**0.5**	**0.5**	**1**	**0.5**	**1**

Objectives

The objective is to develop the MACH Platform (**MaP**) which will be a web-driven application that will store all the information and analysis/simulations gathered through the whole project. MaP will be able to store, in a well organized format, relative data for each monumental test site and all the partners will be able to access and contribute with their work to the system. MaP will guarantee the quick and easy exchange of data between the partners, the monitoring of the progress on each relevant work package. It will be a valid contribute to the dissemination/publicity of the work done..

Description of work

Task 4.1 Data format establishment – [11 mm]

One of the key actions in this Task will be to define in the early phase of the project (Kick-off meeting) a common data interchange format, which should allow easy interchange of data among partners, unified processing and integration. For the construction of the MACH Platform (MaP) it is necessary to define and establish, with the agreement of all the partners, which data will be inserted into and criteria for their encoding. The process will remain open to the incorporation of new possible parameters arising during the work of the project. The data format will be used in the construction of the relational database that will be the background application for their storage into the platform (*backbone* of Mach). Also, this information will be used to the design of the platform itself since the capabilities of MaP are strongly related with the content that will be stored.
To later build up the final objective, the expert system (DST) that will assist end users in scheduling maintenance programmes of monumental buildings, all the data in the field of damage and material decay of functional, decorative elements and some types of the movable heritage that it may host must be coded and parameterised. This is not an easy task. First it will require a complete knowledge, partially gained through WP2 and with a critical examination of bibliography (WP3), of the different local **parameters** that can affect a monument as a "whole : environmental and climatic impact (temperature, humidity, solar irradiance, wind load, rain impact, pollution) on constitutive and external or internal materials (stresses and cracks on masonry stones, bricks, mortar, wall paintings and timber) and on structures due to natural or man-made hazards (earthquake, flooding, traffic and visitors); together with chemical, biological and physical data needed for the characterisation of materials and of their state of conservation (composition of the decayed surfaces due to the weathering and the influence of climate).
Most of these data should come from a series of diagnostic tools having as output digital, analogical, electrical and optical signals. In parallel, as a monument is something more complex, stratified and articulated than just a simple series of diagrams, these kinds of data will be integrated with information regarding the history, architectural style and documented past intervention. All this information will be classified and stored as the bibliographical source of the platform. The platform can contain raw data, but also processed and filtered data.
Partners involved:All but UPC.

Task 4.2 Design and development of the platform – [6.5 mm]

The concept on which is based the construction of the web-driven MACH Platform (see MaP illustration on pag 14) is to organize in a single structure, accessible via internet, all the data collected and produced in the activities of the project. These are stored in relation data base and used to feed the simulating tools and the final expert DST. Furthermore, it will contain the specification of the common interfaces with the different monitoring devices for web-based data transmission (from the sampling devices to the remote data repository); the data mapping modes for presenting those data plotted on the 3D and/or 2D representations of the monument; the visualization of functionalities provided from the remote sensors.

The development of the platform consists of two parts:
a) The creation of the relational database that will store all the data
b) The development of the web application that will give access to the database and also may contain other remote software such as the Simulating tools (WP8) and the expert Decision Support Tool (WP9).

a) Relational Database: The relational database of the platform will store the data coming from each monumental bench mark site as a *Discrete Monument Project*. More specifically, WP2 will contribute

with general characterization of the monument as a whole (documentation, history, visualization etc.), WP3 will provide data from standard and non-standard testing procedures, WP6 will produce all the monitoring measurements of the monuments both from stationary (WNS and FOS) and portable diagnostic tools (i.e. moisture diffusion, deformation, stresses) and WP8 will provide ready made numerical simulations of the monument. All these data will be available for dissemination (WP10) and will also be used by the Decision Support Tool (DST) of WP9.
The construction of the database is divided into the following three distinct steps:

1. Construction of the Entity-Relations (E-R) diagram where all the parameters that will be inserted are recorded and the relations among them are defined (this step is strongly connected with Task 4.1).
2. Construction of the Relational diagram in which the parameters defined in the previous step are organized into tables that are related among them with keys which ensure the integrity of the database.
3. Construction of the database based on the Relational Diagram of the previous step. The database will be developed in *SQL* which is a well established relational database system.

b) Web Application: The web application that will be the visual interface between the database and the users/partners will be developed in the *Java Language*. The development will be based on the Model-View-Controller 2 (MVC2) architectural pattern which is a widely accepted technique for the development of dynamic web applications. *Figure 1* illustrates a diagram of the MVC2 and how each part interacts with the others.

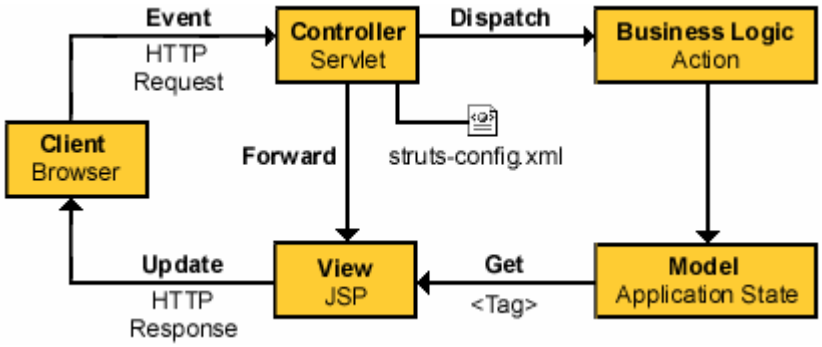


Figure 1: The Model-View-Controller 2 architectural pattern

The partner sends a request to the platform where a central controller dispatches the request to the appropriate action as well as reuses the relative view component (the jsp web page). The action calls the model, which is the application that performs all the business logic (connect to the database, perform calculations etc) and the result is made available to the view component. The platform will also be able to visualize the data stored into the database (e.g. producing dynamic charts) as well as perform a second level elaboration of the data (e.g. expert decision). Partner TUC will develop the database as well as the web application.
The platform will be composed by to main components:

- a data visualizer component, whose goal will be to present interactively the status of the monument by mapping all the data gathered by the sensors and investigation tools in a geo-referenced manner;
- an interface to the expert system (DST), which will support the end users in their decision making process, related to damages and material decay of functional and decorative elements of a monument.

The beta release of the Web-driven Interactive MACH Platform (M12) will be implemented using standard graphics and web libraries running on the standard PC platform. This release will be distributed to the partners for a first round of assessment and verification and the first version will be established (M19). The final release of the Web-driven Interactive MACH Platform, revised according to the feedback of the partners (bug fix and user interface revision) will be completed on M31. The

MaP will be located at TUC web application server and accessible, via internet, by partners with password.

A structure similar to the MACH Platform is non-existent in the European Cultural Heritage community and will give the following benefits:

1) Integration of all information in a web-driven European platform
2) Networking of involved partners and their activities finalized to solve complex optimization problems of Monument Conservation
3) Attraction of new stakeholders outside the present consortium

Partners involved: ICVBC, TUC

Milestones & Deliverables

ML4 – Data homogenisation and definition of their format
D4.1 - Web driven Interactive MACH Platform – First release, M19
D4.2 - Web driven Interactive MACH Platform – Final release, M31

Workpackage number	**5**	**Start date or starting event:**		**T1**		
Workpackage title	**Innovative diagnostic tools**					
Activity type[1]	**RTD**					
Participant n°	**ICVBC**	**UPV/EHU**	**KUL**	**TUC**	**SINT**	**SMARTEC**
Person-months per participant	**3**	**7**	**2**	**4**	**25,5**	**6**
Participant n°	**INNOWEP**	**ITAM**	**IPPT**	**BAM**	**UMINHO**	**Total**
Person-months per participant	**9**	**2**	**3**	**3**	**2**	**66.5**

Objectives

Design and development of innovative tools for the damage assessment, diagnosis and monitoring of the cultural heritage. These tools are to be applied in long term and periodic monitoring of the monumental bench mark sites

Description of work

The simplest way to monitoring historical monuments is by visual inspection. The few non-visual methodologies for long term monitoring make use of wired sensor techniques, which are relatively expensive, vulnerable to damage, invasive and time consuming to install.
A monitoring programme must be based on simple, reliable and low cost diagnostic tools. This sequence is the key for the success of the project and the effective diffusion and adoption of MACH's results.
Systems based on wireless sensor networks should be both cost efficient and easy to install and sensors with low price are essential for such monitoring systems.

In the case of the periodic monitoring of historic buildings non destructive (NDT) or minor destructive (MDT) techniques are required, in order to avoid invasive tests for the damage assessment, diagnosis and monitoring.
NDT can be helpful in finding hidden characteristics (internal voids and flaws and characteristics of the wall section) which cannot be known otherwise than through destructive tests. Up to now most of the ND procedure can give only qualitative results; therefore is asked to interpret the results and use them at least as comparative values between different parts of the same structure or by using different ND techniques.
In general there is a need to develop easy-to-use and cost effective measurement systems. In this project we propose the following innovative (NDT/MDT) test methods:

- The long term monitoring of material and structural performance using a Wireless Sensor Network
- The on-site stresses measurements, with low damage to the structure (avoiding the use of destructive flat jacks)
- The surface pattern analysis using portable diagnostic optical device for stone surface damage evaluation.
- The optimized automated active thermography system (NDT) for contactless detection of voids, delaminations and in homogeneities in the near surface region of masonries
- New NDT methodologies to in-situ characterisation of inorganic and organic compounds deposited and trapped on the surface of stones, bricks and mortars
- Innovative NDT system to estimate biodeteriogens on surface of materials.

The portable instruments for NDT and MDT measurements improved or developed in this WP and the Wireless Network Sensors will be applied for the extensive monitoring campaign at the Common Monumental test site in Ortigia (Sicily, Italy) and in related benchmark sites.
The following Tasks are foreseen, divided in some subtasks:

Task 5.1 - Wireless Sensor Networks System
Task 5.2 - On site Damage evaluation

Task 5.1 - Condition monitoring of a monument using Wireless Sensor Networks [18 mm]

Existing monitoring systems use traditional wired sensor technologies and several other devices that are time consuming to install and relatively expensive. Typically they are using a small number of sensors which are connected through long cables and are normally installed only on a few important historical monuments. A wireless monitoring system with MEMS (Micro-Electro-Mechanical-Systems) could reduce these costs significantly. MEMS are small integrated devices or systems combining electrical and mechanical components that could be produced for a very low price.
Each sensor device (mote), which is itself a complete, small measurement and communication system, has to be powered and cost optimized. Using multi-hop techniques, the data of the sensor network can be transmitted over short distances from each hop to a base station on site. At the base station the data items are collected and stored in a Central Unit (CU) for subsequent analysis. If the CU detects a hazardous condition by analyzing the data, it raises an alarm message. The central unit also allows for wireless administration, calibration and reprogramming of the sensor nodes in order to keep the whole system flexible. These data, once processed, will be accessible by a remote user, collect and stored in the MaP.
Each mote is composed of one or more sensors, a data acquisition and processing unit, a wireless transceiver and a battery power supply.
This task will be divided in 3 subtasks:

– Subtask 5.1.1 - Application of the Wireless Sensor Network (WSN) technology to the long term monitoring.
– Subtask 5.1.2 - Development of a diagnostic tool for long term monitoring of deterioration phenomena and damages caused by vibration effects, connected with the WSN.

– Subtask 5.1.3 - Comparing and evaluating the results from conventional cable based monitoring systems with the new WSN based long term monitoring system.

Subtask 5.1.1 –Application of the Wireless Sensor Network (WSN) technology to the long term monitoring

Application of Wireless Sensor Network (WSN) technology to the Maintenance of Cultural Heritage allows achieving two different goals:

- several different parameters can be collected in a very low-invasive way,
- using a larger deployment of sensors for a better "monument as a Whole" monitoring.

The target of this activity will be to design a WSN prototype, able to perform a Cultural Heritage structural and non-structural monitoring.
This study will investigate the typology and the different technologies of structural and non-structural transducers, and it will take care of to integrate these particular sensors in a WSN.
This achievement will be carried out through the following main steps:

a) Investigation about the typology and different technologies of the transducers, useful to be used in a long-term monitoring system with the WSN Technology, both for structural and non structural monitoring; preliminary study of the electronic interfaces between motes and sensors useful for cultural heritage application.
   Four different typologies of parameters will be considered:
   Mechanical: strain, deformation, crack opening and vibration
   Environment: wind, emperature, relative humidity and solar irradiance
   Precipitation: rain impact evaluation (experimental)
   Gas pollution: CO_2, SO_2, NO_2, O_3,

b) Study of physical WSN infrastructure (Hardware),
   It is necessary to investigate the WSN architecture which better fulfils the proper monitoring in order to identify the time-dependent global behaviour of a Monument. The study has to investigate how to interface the transducers with the WSN motes, the data reliability, the life time of the devices and the wireless network configurations.

   The following issues will be studied:
   - Network topology which better matches the building monitoring needs
   - Definition of data collection methodology and timing
   - Hardware power consumption optimization
   - Integration of the transducers on the single nodes (motes)

c) Definition of the specifications of the remote control, protocols and interfaces to communicate to access point

d) Development of procedures and algorithms in order to optimize network resources and reliability of collected data (Software).
   It will take care to check the proper network functioning and configuration. The collected data have to be delivered to the central elaboration system, in order to realize the common MaP and model, which is the backbone of the whole project. WSN have strong power consumption constraint, so it is important to optimize algorithms in order to avoid resource wasting.

e) In-house testing of a long – term monitoring system with WSN technology
   The developed system, in the prototype configuration, will be first tested in the laboratory and after it a prototype will be installed in a monumental building in Florence (S. Giovanni Baptistery), before the final application in Ortigia and in the Porto Cathedral (WP6)

Partners involved : ICVBC/UNISI, SINT/HTS

Milestones:

- ML5.1 – Design, implementation and realization of a Wireless Sensor Networks (WSN)

- WSN Software (tinyOS platform) and Data managing software (Linux and Windows platform).
- Survey of the transducers which can be used in a long-term monitoring system of a monument with the WSN Technology.
- Design and implementation of wireless sensors (motes) interface, able to interconnect motes with different transducers.
- In-house test report of the WSN monitoring system

Selected references:

A. Bemporad, F. Gentile, A. Mecocci, F. Molendi, and F. Rossi, "A wireless magneto-resistive sensor network for real-time vehicle detection," in Proc. European Wireless Sensor Network Conf., Delft, The Netherlands, 2007.

A. Mecocci, T. Capasso "Generative models for license plate recognition by using a limited number of training samples" IEEE International Conference on Image Processing October 2006, Atlanta (USA)

A. Abrardo, A. Alessio, P. Detti, M. Moretti, "Centralized Radio Resource Allocation for OFDMA Cellular Systems," International conference on Communications June 2007, Glasgow (Scotland)

S. Di Cairano, A. Bemporad, and A. Caldelli, "Moving target detection and tracking in wireless sensor networks," in Proc. European Control Conf., Kos, Greece, 2007.

A. Abrardo, "Non-coherent MLSE Detection of M-DPSK DS-CDMA Wireless Systems with Antenna Arrays," IEEE TRANSACTIONS ON VEHICULAR TECHNOLOGY, June 2003

A. Bemporad, F. Borrelli, and M. Morari, "Model predictive control based on linear programming The explicit solution," IEEE Trans. Automatic Control, vol. 47, no. 12, pp. 1974–1985, 2002.

A. Abrardo, M. Barni, C. Mosquera, F. Perez-Gonzalez, "Improving the Performance of RDM Watermarking by Means of Trellis Coded Quantization," IEE PROCEEDINGS-VISION IMAGE AND SIGNAL PROCESSING, October 2006

A. Bemporad, G. Ferrari-Trecate, and M. Morari, "Observability and controllability of piecewise affine and hybrid systems," IEEE Trans.Automatic Control, vol. 45, no. 10, pp. 1864–1876, 2000.

Subtask 5.1.1 – Development of a diagnostic tool for long term monitoring of deterioration phenomena and damages caused by vibration effects.

Design and development of a vibration measurement system suitable to be connected with the Wireless Sensor Network. The measurement system will be composed by sensors, microprocessor, data logging and motes. It will be equipped with an independent battery power supply. Targeted sampling ratio is up to 300Hz (it is the maximum sampling rate useful for building application). The data will be transferred to the wireless network system for monitoring a monument as a whole. The development process will consist of testing of sensors taking advantage of new intelligent materials and technologies in laboratory as well as on site and data measurement and analysis.

Partner involved : ITAM/SINT

Deliverable:

D5.1.1 – On site vibration monitoring device

Zembaty Z. Dynamic identification and monitoring of structures under seismic excitation, I-SAMCO workshop: "Advances ins structiraů monitoring of historical and modern structures", Prague 18-19, September, 2006

Demarie G., Link M., De Stefano A., Napoli P., Pernice F., Macera M.,Vibration testing on historical structures. I-SAMCO workshop: "Advances ins structiraů monitoring of historical and modern structures", Prague 18-19, September, 2006

Robert-Nicoud, Y., Raphael, B. and Smith, I.F.C. "System Identification through Model Composition and Stochastic Search" J of Computing in Civil Engineering, Vol 19, No 3, 2005, , pp. 239--247

Saitta, S., Raphael, B. and Smith, I.F.C. "Data mining techniques for improving the reliability of system identification" Advanced Engineering Informatics, Vol 19, No 4, 2005, pp 289-298.

Subtask 5.1.2 - Comparing and evaluating the results from conventional cable based monitoring systems with the new WSN based long term monitoring system

This task aims at comparing and evaluating the results from conventional cable based monitoring systems with the new WSN developed in this project, in real case studies and in situ conditions for short term and long term monitoring.
Using the WSN for both dynamic and long term monitoring some difficulties can arise related with the synchronization, high sampling rates and the power supply. The system can only be validated if a comparison between the classic cabled system and WSN sensors is made.
Besides, the design of WSN with MEMS is centred on the innovation with clear advantages for diagnostic of possible deficiencies in historical constructions as they are more economical and overcome difficulties related to invasive positioning on a historical construction. However their application is in an exploratory phase and care has to be taken in their adequacy for dynamic monitoring.
This task includes the installation of a wireless system and the actual monitoring for the period of three years of one Portuguese monument: the Cathedral of Porto (South tower). This monument is actually under investigation by University of Minho with conventional sensors.
The results will be compared with theexisting conventional monitoring systems. This task includes a feasibility study aiming at understanding if these devices are applicable for dynamic identification and / or sonic investigations, including the advantages in performance, cost, connectivity, etc.
Partners involved : UMINHO – ICVBC - SINT

Milestone:

ML5.2 - Validation of the developed wireless systems, with respect to conventional systems

Deliverables:

D5.1 - Open Wireless Sensor Network monitoring System

Selected References:

Lourenço, P.B., Assessment, diagnosis and strengthening of Outeiro Church, Portugal, Construction and Building Materials, 19(8), p. 634-645 (2005)
Ramos, L.F., de Roeck, G., Lourenço, P.B., Campos-Costa, A., Vibration based damage identification of masonry structures, in: Structural analysis of historical constructions, Eds. P.B. Lourenco et al., McMillan, p. 641-649 (2006)
Ramos, L., De Roeck, G., Lourenço, P.B., Campos-Costa, A., Damage identification based on vibration measurements applied to masonry structures, ISMA2006 International Conference on Noise and Vibration Engineering, Leuven, Belgium, p. 925-940 (2006)
Ramos, R.F., Casarin, F., Lourenço, P.B., Modena, C., Dynamic identification of the Qutb Minar, New Delhi, India, International Operational Modal Analysis Conference Workshop, Copenhagen, Denmark, CD-ROM, 8 pp (2006)
Oliveira, D.V., Ramos, L.F., Lourenço, Roque, J., Structural monitoring of the Monastery of Jerónimos, in International Conference on the 250th Anniversary of the 1755 Lisbon Earthquake, Lisbon, p. 466-473 (2005)
Ramos, L.F., Lourenço, P.B., Costa, A.C., Operational modal analysis for damage detection of a masonry construction, Proc. 1st Int. Operational Modal Analysis Conference, Copenhagen, Denmark, p. 495-502 (2005)

Task 5.2 – Portable systems for on site Damage evaluation [48.5 mm]

This task will be divided in 5 activities:

- 1 - Portable diagnostic devices for masonry damage evaluation (hole drilling method, drilling resistance method, CoDit technique)
- 2 - Portable diagnostic optical device for masonry surface damage evaluation.
- 3 - Optimized automated active thermography system.
- 4 -New NDT methodologies to in-situ evaluation of the inorganic and organic compounds deposited and trapped on masonry surfaces.
- 5 -- Innovative system to estimate biodeteriogens on masonry surfaces.

.1 - Portable diagnostic device for masonry damage evaluation

In order to establish the building integrity or the load carrying capacity it is important to investigate the local state of stress and to analyze the mechanical and chemico-physical characteristics of the constitutive material.
The in-situ mechanical test method now available for the onsite stress measurement is the flat-jacks method, which is to be considered as destructive. It is of major importance the development of a MDT method in order to strongly reduce the damage produced for the deduction of the on site stresses.
A portable, compact and battery operated equipment will be developed which will have the capability to measure the following parameters, in the same test:

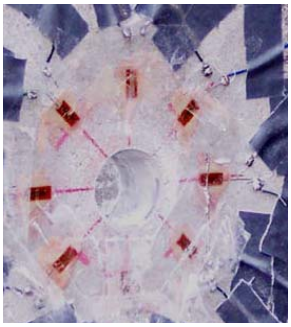
- onsite stresses with the hole drilling strain gauge method.
- drilling resistance with the evaluation of UCS in stone materials, bricks and in mortars

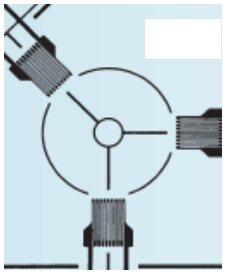
The system will have also the capability to prepare samples for the Compact Diagnostic Test (CoDiT).

The device will be composed by: a portable microdrilling device with integrated electronics, strain gauge amplifiers, a software for data acquisition and data analysis. The drilling tool will be derived from the one used in the McDUR and DIAS projects and will be capable of advancing at constant speed and constant penetration rate. The partner SINT Technology will design and develop the instrumentation

The techniques used in this portable instrument are the following

- The Hole Drilling strain gauge technique will allow to measure the on site stresses by drilling a small hole or a small core (8-10 mm diameter). The strains will be measured with strain gauges placed on the surface.



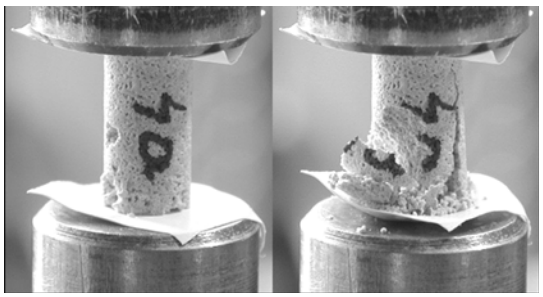


Application of hole drilling on a masonry *Small diameter strain gauge rosette for improve hole drilling test*

- The Drilling Resistance measurement allows the measurement of the drilling force while drilling a hole with constant rotational speed and constant penetration rate. This technique will be useful for evaluating the strength of stone, bricks and mortars. In the case of ancient mortars this technique could be very powerful to detect the quality of mortar joints. Some algorithms will be used for back-analysis of microdrilling results for the determination of the strength properties of rocks, monumental stones and artificial materials (mortars, concretes etc)

Microdrilling tool for non destructive measurements

- The Compact Diagnostic Test (CoDiT) method to determine mechanical characteristics of the materials from the structures where diagnostic and/or monitoring equipment is to be installed. CoDiT makes use of micro-cores drilled out of masonry during the residual stress measurement. Then micro-cores are tested to measure material's Uniaxial Compressive Strength (UCS) and Indirect Tensile Strength (ITS) as well as elasticity modulus and ultrasonic waves propagation.



Microcore of 6 mm diameter in old brick *Uniaxial compression of a slender cylinder.*

This portable testing equipment will have the advantage performing, the HD test, DR test and CoDiT microcoring during the same test activity. The system will have the capability of evaluating the stress profile versus depth, using the technique of the fine increment hole drilling, by acquiring a lot amount of measurements versus depth
A calibration technique will be developed for the previous method using a laboratory compression test. A calibration specimen will be designed and compression tests will be conducted by measuring the strains before and after drilling

The validation of the small hole drilling technique for stresses measurements in stone masonry and in brick masonry will be done by the UPV/EHU Partner. In order to check the technique by reducing as much as possible the dimensions of drill, twenty stone samples (25 cm x 25 cm x 40 cm) and twenty five brick masonry samples (40 cm x 40 cm x 50 cm) simulating existing masonries will be tested under load in laboratory conditions.
The IPPT partner will collaborate to the integration/adaptation of the CoDiT technique into the portable measurement system. This technique will allow the determination UCS, the Indirect Tensile Strength (ITS), and the elasticity modulus. The elasticity modulus and Poisson's ratio are necessary for the onsite stress calculation
The partner TUC will develop the software development and will validate the algorithms for back-

analysis of microdrilling results for the determination of the strength properties of rocks (UCS, TCS and E), on monumental stones and artificial materials (bricks, mortars etc). This software tool is to be integrated in the DRMS.

Partner involved: SINT, UPV/EHU, IPPT, TUC

Selected References:

Standard Test Method for Determining Residual Stresses by the Hole-Drilling Strain-Gage Method. ASTM 837-01 Standard. American Society for Testing Materials.

Sánchez-Beitia S. Stresses analysis at the Altes Museum of Berlin by means of the Hole Drilling Technique. Construction and Buildings Materials Journal (2006). Elsevier Ed.

Barrallo J, Zulueta A, Sánchez-Beitia S. The Donostia Method for stress measurements in architectural heritage. STRAIN (Journal of British Society for Strain Measurement) 1999; 35 (3): 107-112

Valentini E., Vangi D., "Procedura di prova nell'analisi delle tensioni residue nello spessore con il metodo della rosetta forata", Atti del 22° Convegno Nazionale AIAS, Forlì 1993, pp. 471-478.

Valentini E., "An automatic system for measuring non-uniform residual stress by the hole drilling Method", XIII IMEKO World Congress, Torino settembre 1994, pp. 1904-1909.

Valentini E., Benincasa A., Baggiani M., Brogelli S., "Evoluzione della tecnologia di foratura ad alta velocità per la valutazione delle tensioni residue con il metodo della rosetta forata", Atti del XXXIV Convegno Nazionale AIAS, Milano 14-17 settembre 2005, pp. 1627-1636.

Skłodowski, M. 2006. Compact Diagnostic Test: outline of historical monuments testing procedure. IFTR Reports, 3/2006, Warszawa: IFTR.

Tiano, P. and Filareto, C. and Ponticelli, S. and Ferrari, M., and Valentini, E. 2000. Drilling force measurement system, a new standardisable methodology to determine the "superficial hardness" of monument stones: prototype design and validation. Int.Journal for the Restoration of Buildings and Monuments, 6(2), p. 115-132.

Skłodowski, M. 2006. Quasi-non-destructive testing of historical structural materials using micro-cores. In P.B. Lourenço, P. Roca, C. Modena, S. Agrawal (eds.), Structural Analysis of Historical Constructions, New Delhi 2006, ISBN 972-8692-27-7 (in print).

Stavropoulou M.C., Giannakopoulos, K. and Exadaktylos G.E. (2005)., A theoretical and experimental study of rock cutting J. Mech. Behavior of Materials. Vol. 16, Nos 1-2, pp. 131-150.

Exadaktylos G., Tiano P. and Filareto C. (2000). Validation of a model of rotary drilling of rocks with the drilling force measurement system. Internationale Zeitschrift für Bauinstandsetzen und Baudenkmalpflege, 6. Jahrgang, Aedificatio Publishers, Heft 3, 307-340.

http://minelab.mred.tuc.gr/dias/

G. Beer and G. Exadaktylos, Consideration of geological conditions in numerical simulation, Guimares, Key Note Lecture, In 5th International Workshop on Applications of Computational Mechanics in Geotechnical Engineering, University of Minho,Guimarães,Portugal,

Milestones:

ML5.3 – Design, and development of portable diagnostic tools

- Test Procedure for the small hole drilling technique for stresses measurements in stone masonry and in brick masonry
- Laboratory test report for the small hole drilling technique for stresses measurements in stone masonry and in brick masonry
- Laboratory test report for the CoDiT technique for material strength and modulus of elasticity in stone masonry and in brick masonry

Deliverables:

D5.2 - Portable diagnostic devices for masonry damage evaluation

D5.2.1 – HD - Hole drilling

D5.2.2 – DR - Drilling Resistance

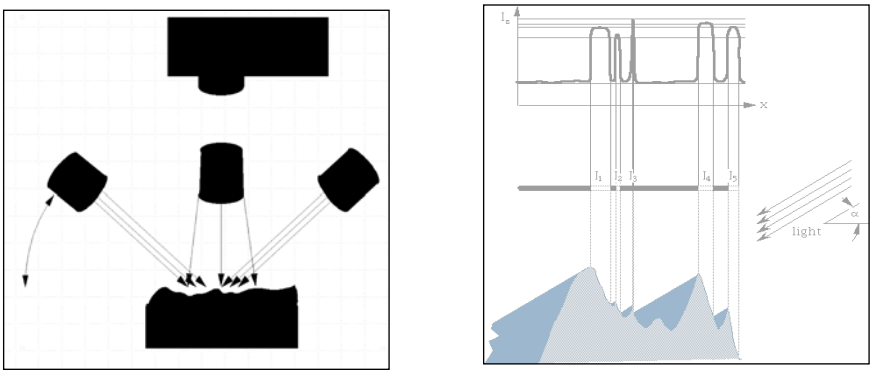
D5.2.3 – CoDiT – Compact Diagnostic Test

.2 - Portable diagnostic optical device for surface masonry damage evaluation

Development of a quick and easy to use portable device for on-site-monitoring. Hereby it will be possible to make measurements of surface parameters and visual properties (3D- surface topography and visual RGB). The technique used in the portable instrument is based upon shade from shading and 3 images are taken under defined light conditions from different directions. These images after elaboration will produce a 3D Optical Roughness Image of the tested area in grey scale for the z axis. Value of roughness can be derived for any x-y point. Dedicated software will be developed for images analysis in order to follow in time the same testing surface and to elaborate the Surface Pattern Index.

The device will consist of:
- Measuring head
- notebook and software for test management and data acquisition and storage
- Analytical software for optical and visual elaboration.

It will work independently from any external power supply. The system is able to document and analyse surface changes (deposit and loss), cracks and erosion or spalling, but also changes in the colour.



Surface meter measuring head and roughness profils

Partner involved: INNOWEP

ML5.4 - Software for the evaluation of changes in visual and optical roughness, and validation of the testing procedure for the measurement of the Surface Pattern Index.

Deliverables

D5.2.4 - Portable diagnostic device for optical surface masonry damage evaluation

.3 - Optimisation of an automated active thermography system (BAM)

Active thermography is based on actively heating up the surface of the structure under investigation and observing the cooling down behaviour with an infrared camera as a function of time. As voids, delaminations and other inhomogeneities close to the surface have an influence on the thermal properties of the bulk material; these might be located at the surface as an increase or decrease in temperature related to the sound area. By analyzing the cooling down behaviour of these defects as a function of time and frequency, qualitative as well as quantitative information is gained about geometry, depth and type of the defect. This technique is completely non-destructive, if a moderate heating of the surface is considered.

The target of the investigations performed in MACH will be an optimisation of this technique and the development of a prototype considering the needs and limits of applications to Cultural Heritage structures. The complementary application in combination with other destructive, minor-destructive and non-destructive will be analysed and the integration into the MACH strategy will be performed.

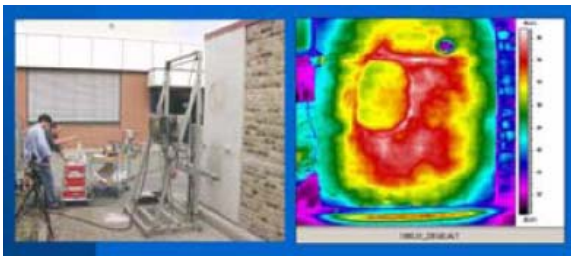
The required equipment is based on an infrared camera enabling periodic recording of thermal images with a good thermal resolution.

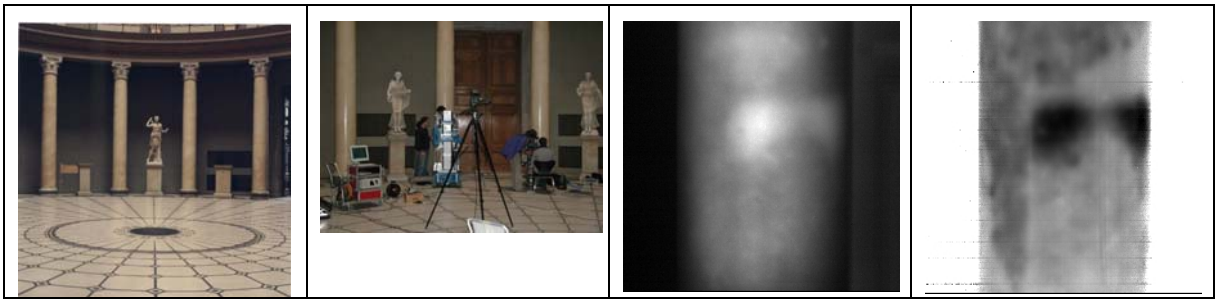
These investigations will be performed in x steps:

- Hardware: Selection of the appropriate heating unit for the investigations of sensitive surfaces (paintings, thin plaster etc.) by considering thermal properties of the surface layers and the bulk material, type of defects, environmental conditions (moisture, humidity, air movement, temperature, etc), integration into an automatic system
- Software:
  - Adaption of software of data recording to the heating system
  - Data analysis concerning contrast curves in time domain and frequency domain, calibration of frequency scale to depth scale
  - Data fusion with data recorded from complementary methods, direct superpositioning of the single data sets
- Systematic investigations in laboratory:
  - Influence of thickness of plaster or depth of delaminations
  - Influence of paintings/surface on quantitative data
  - Influence of moisture content
  - Influence of thermal properties of the material

  Thus, up to 10 specimens will be tested with different layers of plaster and paintings and including different simulated delaminations.
- Integration into MACH strategies: Combination with other methods, case studies

The validation of the methods concerning the depth of delaminations will be performed in WPs 6.2





L*eft: Rotunda of the Altes Museum with plastered sandstone columns. Left Middle: Performance of thermography measurements. Right middle: Thermogram at a selected area after 5 min heating. The temperature range was scaled from 20 to 30 ^{o}C. The delaminations appear as white area (high temperature). Right: Phase image of the same area at 5.56 x 10^{-4} Hz. The delaminations appear as dark area.*

Active thermography (from Onsiteformasonry project)

Partner involved: BAM

Deliverables

D5.2.5 – Optimized automated active thermography system (AT)

Selected References:

- Maierhofer, Ch., Arndt, R. and Röllig, M., Influence of concrete properties on the detection of voids with impulse-thermography. Infrared Physics&Technology
Volume 49, Issues 3, January 2007, pp. 213-217.
- Maierhofer, Ch., Arndt, R., Röllig, M., Rieck, C., Wather, A., Scheel, H. and B. Hillemeier , Application of impulse-thermography for non-destructive assessment of concrete structures , Cement & Concrete Composites 28 (2006) 4, pp. 393-401.
- Maierhofer, Ch., Arndt, R., Borchardt, K., Hasenstab, A., Röllig, M. and J. Wöstmann , Structural assessment with radar and active thermography , in: Radic, J., Rajcic,, V., Zarnic, R. {(eds.);} Proceedings of the International Conference Cultural Heritage, The Construction Aspects of the Heritage Protection , Dubrovnik, Croatia, 14-17 October 2006, pp. 77-85.
- Maierhofer, Ch., Brink, A., Röllig, M. and H. Wiggenhauser, Quantitative impulse-thermography as non-destructive testing method in civil engineering - Experimental results and numerical simulations, Construction in Building Materials 19 (2005) 10, pp. 731-737.
- Maierhofer, Ch., Brink, A., Röllig, M. and H. Wiggenhauser, Transient thermography for structural investigation of concrete and composites in the surface near region, Infrared Physics & Technology 43 (2002) pp. 271-278.
- Maierhofer, C., Brink, A., Röllig, M. and H. Wiggenhauser, Transient Thermography for Non-destructive investigation of building structures in the near surface region, in: Proceedings of the Workshop of the RILEM Technical Committee 177MDT: Site control and non-destructive evaluation of masonry structures and materials, 13.-14. November 2001, Mantova, Italy, pp. 251-261.

4 - New NDT methodologies to in-situ evaluation of the inorganic and organic compounds trapped on the surface of stones and mortars

New NDT methodologies to in-situ evaluate the inorganic and organic compounds deposited from environment and trapped on the surface of masonry materials will be developed using a new extraction methodology. The extracted compounds will be sent to the laboratory to perform an off-site analysis.
The proposed new NDT extraction methodologies are:

1) The extraction of soluble metals deposited in the surface or in the pores of natural and artificial stones and/or walls by means of a "poultice" having an anion exchanger in the EDTA form, a contact solution of low concentration in EDTA, and a non reactant polar binder. The wet poultice requires 5 cm diameter and should be kept in contact for 24 hours on the surface of the material to be analysed. The metals of soluble inorganic compounds are complexed by the EDTA (anionic complexes) and exchanged in the anionic resin together with common anions like chlorides, nitrates, etc. The extracted metals and oxianions will be then analysed directly on the anion exchanger by SEM/EDS coupled to microRaman (in the same instrument); this measurements are the basis of the new NDT protocol. Part of the anion exchanger will be then eluted and the anions will be analysed by Ion Chromatography. The concentration of nitrates and sulphates obtained by both techniques (SEM/EDS+Raman and Ion Chromatography) should be coincident in order to validate the NDT results
2) The development of a MDT methodology to take a microsample (100-500 mg) and extract the soluble salts with water applying sonication. Then the anions and cations will be quantified by Ion Chromatography. This procedure is intended to be an alternative to the high time consuming NORMAL 18/83 method to estimate soluble salts from mineral phases
3) The development of a NDT method to extract (focussed sonication) non polar compounds in

dichloromethane followed by GC-MS analysis to identify and quantify organic compounds. Also the solid residue obtained after evaporation of the solvent will be used to perform FT-IR analysis. These two analytical techniques will allow us to unequivocally identificate practically all the organic compounds present in the surfaces of stone materials

4) The use of a MDT procedure to collect the degraded grains on the surfaces to perform on them a microanalysis using the coupled instrument SEM/EDS-microRaman to identify non soluble inorganic mineral phases

Partner involved: UPV-EHU Group of Environmental Analytical Chemistry.

Deliverables

D5.2.6 – Optimized on site extraction methodologies for the evaluation of surface chemical deposits

Selected References:

M. Pérez-Alonso, K. Castro, I. Martínez-Arkarazo, M. Angulo, M.A. Olazabal and J.M. Madariaga, Analysis of bulk and degradation inorganic products of stones, mortars and wallpaintings by portable Raman microprobe, Analytical and Bioanalytical Chemistry, 379, 42-50, 2004

K. Castro, P. Vandenabeele, M.D. Rodríguez-Laso, L. Moens and J.M. Madariaga, Micro-Raman Analysis of Coloured Lithographs, Analytical and Bioanalytical Chemistry, 379, 674-683, 2004

M. Pérez-Alonso, K. Castro, M. Alvarez and J.M. Madariaga, Scientific Analysis versus Restorer's Expertise for diagnosis prior to a restoration process: The case of Santa Maria Church (Hermo, Asturias, North of Spain), Analytica Chimica Acta, 524, 379-389, 2004

J. Sanz, J.C. Raposo, J. Larreta, I. Martinez, A. de Diego and J. M. Madariaga, On-line separation for speciation of Hg in natural waters by flow injection-cold vapour-atomic absorption spectrometry, Journal of Separation Science, 27, 1202-1210, 2004

K. Castro, M. Pérez-Alonso, M.D. Rodríguez-Laso and J.M. Madariaga, On-line FT-Raman and dispersive Raman spectra database of artists' materials (e-VISART database), Analytical and Bioanalytical Chemistry, 382, 248-258, 2005

L. Bartolomé, E. Cortazar, A. Usobiaga, J.C. Raposo, O. Zuloaga, N. Etxebarria, LA. Fernández, Optimisation of Microwave-assisted Extraction for the Determination of Nonylphenols and Phthalate Esters in Sediment Samples and Comparison with Pressurised Solvent Extraction, Anal. Chim. Acta, 534, 247-254, 2005

L. Bartolomé, E. Cortazar, J.C. Raposo, A. Usobiaga, O. Zuloaga, N. Etxebarria and L.A. Fernández, Simultaneous microwave-assisted extraction of polyciclic aromatic hydrocarbons, polychlorinated biphenyls, phtalate esters and nonylphenols in sediments, J. Chromatogr. A, 1068, 229-236, 2005

.5 – Innovative system to estimate biodeteriogens on surface of stones

To evaluate the damage to historical buildings, monuments or statues from biodeterioration, it is essential to characterize and quantify the organisms involved in such process materials decay. Enumeration and identification of micro-organisms and activity quantification has been done by several techniques. The ecology and physiology of dwelling microrganisms have been studied and used for the evaluation of the biological action and stress that such activity could cause to the material on which they are growing. The application of many of these accurate, non destructive and environmentally friendly techniques, using scientific and technological criteria, will be applied for integrate the study of the "monument as a whole".

The proposed new techniques and methodologies are:

1 - Image Analysis Spectroradiometry of surfaces colonized by organisms is a technique that allows the characterization and quantification of populations and evaluate the damage they could provoke and so to select the appropriate and specific biocontrol measure (Hormaetxe et al., 2005). The implementation of this technique in this new approach should be done via its complementation with

other off-site technologies such as chromatography *(HPLC) photodiode-array detector and fluorescence.* The quantification of photosynthetic pigments and antioxidants and other essential metabolites will allow the estimation of biomass, chemical identification and tolerance mechanisms of phototrophs to survive.

2 - Physiological Profiles of Biodeteriogens. Due to the limitation for the determination of biodeteriogens other than phototrophs, an innovative system based on Biolog "fingerprints", similar to other applied to estimate physiological profiles on soils, will be developed. This system will allow the estimation of physiological profiles at community level in a rapid, cost-effective and easy way, and will permit to see correlations with other non destructive, portable techniques to estimate biomass, and most important metabolic activities under environmental-, stress-, pollution-, substrate-conditions. The *Structural (Biolog System) and Functional Biodiversity of Microbial Populations* of biodeteriogens could be implemented in collaboration with Dr. Garbisu, NEIKER, Bilbao. This can be important to design a more integrated program to control all the microorganisms in the biofilm.

Partner involved: UPV-EHU (Plant Biology and Ecology)

Deliverables:

D5.2.7 - Methodology to estimate biodeteriogens on masonry surfaces

Selected References:

Bartosch, S., Mansch, R., Pinck, C., Bock, E., 2002. Visualisation and quantification of microorganisms on mortar on natural stone by CLSM. In: Galán, E., Zezza, f. (Eds.), Protection and Conservation of the Cultural Heritage of the Mediterranean Cities. A.A. Balkema Publishers, Lisse. Pp. 275-279

Bartosch, S., Mansch, R., Knotzch, K., Bock, E., 2003. CTC staining and counting of actively respiring bacteria in natural stone using confocal laser scanning microscopy. Journal of Microbiological Methods 52: 75-84

García-Plazaola, J.I., Becerril, J.M., Hernández, J., Ninemets, U., Kollist, H., 2004. Acclimatation of antioxidant pool to the light environment in a natural forest canopy. New Phytologist 163: 1787-1801

Hernández, A., Langara, L., García-Plazaola, J.I., Becerril, 1999. Production of phenolic acids in nodulated soybean treated with herbicide glyphosate. Recent Advances in Allelopathy. 335-338

Hernández-Allica, J, Becerril, J.M., Zárate, O., Garbosu, C.., 2006. Assessment of the efficiency of a phytoextraction process with biological indicators of soil health. Plant and Soil 281, 147-158

Hormaetxe, K., Becerril, J.M.,Fleck, I., Pinto, M.,García-Plazaola, J.I., 2005. Functional role of red (retro-carotenoids as passive light filtres in the leaves of Buxus sempervirens L.: increases protection of photosynthetic tissues?. Journal of Experimental Botany, 56, pp. 2629-2636

Pantani, L., Ballerini, G., Cecchi, G., Edner, H., Lognoli, D., Johansson, T., Raimondi, V., Svanberg, S., Tiano, P., Tomaselli, L., Weibring, P., 2000. Experiment on stony monument monitoring by laser-induced fluorescence. J. Cult. Heritage 1: S345-S348

Preston-Mafham , Boddy, L., Randerson, P.F. Analysis of microbial community functional diversity using sole-carbon-source utilisation profiles - A critique FEMS Microbiology Ecology 42: 1-42002

Quader, H. and Bock, E., 1995. Confocal-laser scanning microscopy: a new method to study microorganisms colonizing natural stone. Int. J. rest. Biochem. 1: 295-304

Richaume, A., Steinberg, C., Jocteur-Monrozier, L., Faurie, G., 1993. Differences between direct and indirect enumeration of soil bacteria: the influence of soil structure and cell location. Soil Biol. Biochem. 25: 641-643

Taylor, S. and May, E., 1995. A comparison of methods for the measurement of microbial activity on stone. Stud. Conserv. 40: 163-170

Taylor, S. and May, E., 2000. Investigations of the localsation of bacterial activity on sandstone from ancient monuments. Int. Biodeterior. Biodegrad. 46: 327-333

Tomaselli, L., Lamenti, G., Tiano, P., 2000. Chlorophyll fluorescence for evaluating biocide treatment against phototrophic biodeteriogens. Ann. Microbiol. 52, 197-206

Warscheild, T., Petersen, K., Krumbein, W.E., 1990. A rapid method to demonstrate and evaluate microbial activity on decaying sandstone. Stud. Conserv. 35: 137-147.

Milestones & Deliverables

ML5.1 – Design, implementation and realization of a Wireless Sensor Networks (WSN)
- WSN Software (tinyOS platform) and Data managing software (Linux and Windows platform).
- Survey of the transducers which can be used in a long-term monitoring system of a monument with the WSN Technology.
- Design and implementation of wireless sensors (motes) interface, able to interconnect motes with different transducers.
- In-house test report of the WSN monitoring system

ML5.2 - Validation of the developed wireless systems, with respect to conventional systems
ML5.3 – Design, and development of portable diagnostic tools
- Test Procedure for the small hole drilling technique for stresses measurements in stone masonry and in brick masonry
- Laboratory test report for the small hole drilling technique for stresses measurements in stone masonry and in brick masonry
- Laboratory test report for the CoDiT technique for material strength and modulus of elasticity in stone masonry and in brick masonry

D5.1 – Open Wireless Sensor Network monitoring system
D5.1.1 – On site vibration monitoring device
D5.2 - Portable diagnostic devices for masonry damage evaluation
D5.2.1 – HD - Hole drilling
D5.2.2 – DR - Drilling Resistance
D5.2.3 – CoDiT – Compact Diafnostic Test.
D5.2.4 – SM - Surface Meter System.
D5.2.5 – AT - Optimized automated active thermography system.
D5.2.6 – Optimized on site NTD extraction methodologies for the evaluation of surface chemical deposits
D5.2.7 – NTD Methodologies to estimate biodeteriogens on masonry surfaces

Workpackage number	**6**	**Start date or starting event:**					**Month 10**
Workpackage title	Monitoring of a Construction of the Cultural Heritage "as a whole"						
Activity type[1]	**RTD - Demonstration**						
Participant n°	ICVBC	UPV/ EHV	KUL	TUC	SINT	SMARTEC	INNOWEP	UPC
Person-months per participant	4	9	4	1	10	3	6	2
Participant n°	UN ROMA1	ITAM	IPPT	BAM	TNO	UMINHO	TT	**Total**
Person-months per participant	2	4	6	5	5	3	1	**65**

Objectives
- To elaborate protocols for environmental, structural and material monitoring practises applied on historical buildings and non-structural assets hosted by the construction
- To implement at benchmark test sites diagnostic and wireless monitoring system which by

complementariness of its components, low cost and friendly technologies and protocols configure a new synergetic instrument for monitoring a CH construction as a whole and scheduling its maintenance.
- To monitoring parameters for evaluate structural and non-structural damages, and their mechanisms, and evolution - including environmental deterioration phenomena and decay processes promoted by chemical reactions and biological growth - as a basis for validation and standardisation of techniques and methods
- To create a Data Base for probabilistic Risk Assessment analysis.

Description of work

Over the past few decades the deterioration process on outdoor monuments and architectural heritage has become clearly visible, taking on increasingly alarming dimensions.
Scientific analysis applied to works of art has made a noteworthy contribution in identifying the by-products that can form on monuments and architectural surfaces, as well as in understanding the different mechanisms of deterioration that influence the state of conservation of the whole structure.
It is well known that the main causes of deterioration of materials (stones, woods, metals) are wheatear variables and atmospheric pollutants, while for the structural integrity traffic, earthquake and flooding are the principal factor of risk.
Monitoring of a Construction of the Cultural Heritage "as a whole" calls for accounting for many technologies, knowledge and experience, sometimes having no common denominator and belonging to really separate fields of science. This is due to the very complex nature of Constructions of the Cultural Heritage which, if considered "as a whole", requires involvement and close collaboration of many competences and specialists. To describe a behaviour of the whole construction in a way allowing to model Risk Assessment and estimate Residual Life (WP 8) special care must be taken to monitor all the deterioration driving factors generated by the environment. For this purpose necessary determinations of mechanical properties of structural materials, moisture, salt, particle organic and inorganic pollutants and microrganisms existing in the structural and decorative elements will be done accompanied by environmental loads estimation (wind, temperature, water table, seismisity and paraseismic vibrations, traffic, etc.) must be realized to get comprehensive knowledge about the monument,
Extensive monitoring campaign, to include comprehensively all diagnostic needs for characterise a *Monument as a Whole,* at the Common Monumental test site in Ortigia (Sicily, Italy) and in related benchmark sites will be performed for a deeper analysis of prevailing environmental factors.. This will be, for structural and no structural parameters in continuous for the stationary Wireless Sensor Network (WSN) and the Fiber Optic Sensors system (FOS),and periodical for measuring material parameters, using the portable instruments for NDT and MDT measurements (new and improved). These will be performed, at the time steps ($T_{zero} = T_{17} - T_1 = T_{26} - T_2 = T_{41}$), while the influence of seasonality on some environmental dependent parameters will be monitored at ($T_{zero} = T_{17} - T_1 = T_{26} - T_2 = T_{34} - T_3 = T_{41}$).

Four complementary Tasks are foreseen:
Task 6.1 - Deterioration phenomena and processes: Selection of parameters, methods and protocols definitions**.**
Task 6.2 - Structural diagnostic including Foundations
Task 6.3 - Non-structural diagnostic and materials decay
Task 6.4 - Value of seasonality for on site monitoring determination

Task 6.1 - Deterioration phenomena and processes: Selection of parameters, methods and protocols definitions - [11 mm]

The conservation of outdoor monuments and architectural heritage must be increasingly characterised by a policy of programmed maintenance as a follow-up to restoration treatment. This means fewer invasive and more systematic interventions; and as we all know, this is a practice that still encounters

difficulties in its implementation in each individual country. There are numerous factors behind this, and one of the main ones is the lack of objective data on the *progression of the deterioration.* We all know that the progression is rapid; however, we are not yet able to precisely quantify the deterioration progression on a case by case, context by context, material by material basis. This hinders the formulation of a list of priorities, prevents the optimal use of chronically scarce resources, and restricts timely intervention before reaching the 'point of no return' on truly urgent cases.
The objective is to identify changes in structural and superficial physical-chemical conditions of monumental buildings (as a whole) over time. Monitoring is based on assumptions of cause and effect and the results help identify potential threats and development trends in order to define a Risk Assessment Map and to facilitate maintenance management decisions.
- The first step is to identify the most appropriate parameters for "qualify" the state of conservation of a cultural artefact in order to understand it as whole.
- The second step is to select the most efficient (cost/benefit) device to determine the identified parameter.
- The third step is to establish the most suitable protocol (time interval and methodology) for monitoring the identified parameters.
The monitoring aim will be concentrated on potential threats such as: "structural failures" "loss of materials", "state of preservation", "colour changes" and "texture modification". The quality of monitoring data must be essentially based on *"precise value"* in order to be able to derive trends estimation over time for scheduling a sustainable maintenance programme.

The following decay processes and diagnostic tools are involved in the conservation of the CH:

CAUSES	EFFECTS	PARAMETERS	DEVICES
		CHROMATIC - AESTHETICAL ALTERATION PROCESSES	
- Humidity and Thermal changes - Salt migration - Chemical and Photo reactions - Aerosol pollutants and avifauna dropping - Biological colonization	-Loss of material, cracks and fissures, micro and macro deformation - Surface and conservation treatments modifications -Salt efflorescence and crystallization -Mortars and plaster chemical alteration - Surface particulate deposits - Chromatic and/or aesthetical changes	- Surface Patterns - Chromatic Coordinates - Topography - Micro/macro roughness and structure analysis - Change of visual impression - Intensity distribution	- Digital Standard & - Raking Light - Images Macro - Photos + GIS - Colorimeter -Visual examination - OSA (Optical Surface Analysis)
		PHYSICAL -ALTERATION PROCESSES	
- Humidity and Thermal changes - Salt crystallization - Acid rain and pollutants - Conservative treatments - Underlaying soil instability (clays, water table) - Ground movements	- Displacement of the mortar, cracks and fissures, micro and macro deformation of the surface - Detachment or bending of the mortar - Swelling reactions in mortar - Surface roughness modification - Porosity changes - Cracks and fissures - Inclination	- Micro Vibration - Fissures - Surface Temperature & Humidity -Local distribution of elasticity/plasticity - Topography - Micro/macro roughness and structure analysis - Thermal Diffusion - Sonic or Ultrasonic waves - Surface Micro Profiles	- Accelerometer (X– Y- Z) - Fissurometer - Contact thermohygrometer - Sonic & Ultrasonic equipments - Thermovision - Visual examination UST, OSA - Contact Sponge
		CHEMICAL ALTERATION PROCESSES	
- Humidity and Thermal changes - Chemical and Photo reactions - Aerosol pollutants and	- Surface treatments modification - Mortars chemical alteration - Salts crystalization - Surface particulate deposits	- Chemical Composition - Elemental Composition	- FT-IR - XRF - HPLC - GC-SM - SEM EDAX

avifauna dropping			
BIOLOGICAL ALTERATION PROCESSES			
Biological colonization	Biological settlement and development	Microbial Markers Species identification	- Epifluorescence -Optical Microscopy - SEM Spectroradiometry

SURROUNDING ENVIRONMENT		
CAUSES	**PARAMETERS**	**DEVICES**
Humidity and Thermal changes	Temperature and Humidity	Thermohygrometers sensors The surface temperature allows to calculate the RH at the surface and, consequently, to evaluate the risk of surface condensation and/or crystallization/dissolution cycles of salts eventually present in the material.
Rain, flooding	Water flow	Pluviometer – Rain Impact
Traffic	Vibration	Accelerometer (X – Y- Z)
Earthquake	Intensity	Seismograph
Sun	Sun Irradiance	Photosensors
Wind	Velocity and Direction	Anemometer
Solid particulates pollutants	Composition & Concentration	Particulates Samplers
Gaseous pollutants	Composition & Concentration	Gas sensors, GasTrap & Samplers
Pollen grains, fungal spores, and other biological airborne particles and structures	Composition & Concentration	Aereobiological Samplers

Furthermore, the actual practices of monitoring applied by Monumentenwacht organizations to describe damage and damaging mechanisms with simple visual inspections will be integrated in the MACH Platform together with the MDDS system

It is foreseen to complete existing reference systems (atlases of damage) to cover all relevant factors that can be monitored in structures as a whole. Indicators for measuring change of damage or change of damaging mechanisms with time at given locations will be identified. Then space distribution of damage, damaging mechanisms and indicators through morphology identification will be connected together and further relating this information to change over time will result in definition of monitoring protocols and “instrument”;

Partners involved = ALL

Task 6.2 - Structural diagnostic including Foundations [21mm]

Mechanical properties of structure constituent materials and structural deformations are of primary importance for the existence of a monument "as a whole". Loss of structural integrity, despite of the reason (overload or loss of load bearing capacity or limited load support of a foundation) is the most danger event in monuments life. Thus diagnosis of mechanical parameters of the construction and monitoring of changes in its state must be done in the best affordable way using selected most reliable and efficient methods and protocols. Diagnostic measurements and long term monitoring of structure deformations and its foundation will be done. This includes monitoring of its subsidence and heave, inclination of its structural elements, crack opening and response to the environmental static, cyclic and

dynamic loadings (displacements, accelerations) due wind, traffic, temperature, and ground water level.

The *Hole Drilling Technique* is based in the measurement of the strains originated by relaxation of stresses after the drilling a hole. The technique involves strain gages glued on the surface of a stone of the masonry in the surroundings of the hole. The stresses can be obtained from the recorded strains by means of a well known mathematical scheme. Hole Drilling Technique has to replace to the Flat Jacks Technique for the deduction of the on site stresses in Cultural Heritage. The damage generated by using Flat Jacks Technique cannot be assumed by the most of the structural elements in Cultural Heritage Constructions. It is of major importance the development of a method in order to reduce drastically the produced damage by the deduction of the on site stresses. Even more, the Hole Drilling Technique allows the deduction of Principal Stresses and their directions under any states of load (Compressive or tensile). Until now the Hole Drilling technique in brick masonry includes brick and mortar. This fact has a great importance because the mathematical scheme includes the mechanical constants of masonry. These parameters are influenced by the proportion of mortar and brick extracted by drilling.
According to previous experience the drill dimensions are 36 mm of diameter and 36 mm of depth. These dimensions of the drill cause that the extraction of material includes both brick and mortar. The stresses obtained by means of the Hole Drilling Technique depend on the strains registered after the extraction of material and on the mechanical constants of the masonry. Consequently the extracted material must represent the entire masonry and the proportion of brick and mortar must be controlled. The solutions to solve this problem. The solution adopted is to reducte the drill size in order to extract only brick and to turn the problem to which it takes place for stone masonry. This will also reduce the impact of the method on the masonry structure.

Compact Diagnostic Test and Indentation methods, based on developments made in the WP 5, will be used for on site stress measurements of structural materials.
For displacement and deformation measurements (crack opening. inclinations, horizontal and vertical movements) FOS and WSN monitoring technology (WP5) will be used. Monitoring campaign will be carried out at the Common Monumental test site in Ortigia and in related benchmark sites (defined inWP2) at 3 time steps, while continuous monitoring wireless data transmission for analysis in-between will be made.

Mechanical dynamic loads caused by wind, earthquakes, and paraseismic loads due to everyday technical activity will be measured at the monumental test sites. Dynamic structural response and monitoring of deterioration phenomena and damages will be recorded and significant parameters, including ground transmission function, for dynamic loading of architectural heritage (buildings and valuable details shall be identified. Determination of dynamical properties of both traditional and new (used for strengthening, damping) materials will be done in laboratory using various tool (shakers, vibration table etc.) simulating the natural processes and their application and monitoring of structural behaviour on-site will be used to validate their influence on structural response of the Construction as a whole.

Partners involved EPV/EHU, SINT, IPPT,

Internal structure of buildings elements and development and evolution of deterioration zones will be studied using automatic *radar scanne*r based on technology from ONSITEFORMASONRY, *sonic and ultrasonic* investigations and active thermography (pulse-phase thermography) for the investigation of defects and inhomogeneities in the near surface region. Also damage processes at interfaces (e. g. mortar/stone, joints, leafs) will be studied.
Applications of *infrared thermography* in civil engineering are not limited to the identification of heat losses in building envelopes. Active infrared thermography methods enable structural investigations from one side of building elements up to a depth of about 10 cm. The method is based on the heating or cooling of the surfaces to provide an instationary temperature gradient and thus an instationary heat flow

inside the structure under test. The temperature at the surface is recorded as a function of time with an infrared camera. Voids or delaminations close to the surface with different thermal properties might lead to a thermal contrast at the surface. For qualitative and partial quantitative analysis, the data can be processed in time domain as well as in frequency domain.
Masonry and especially historic masonry has a very inhomogeneous structure containing several different materials (brick, stone, mortar, plaster, wood, metal etc.) with different thermal properties. Thus, *active thermography* is in general very well suited to assess the following testing problems in the surface near region:

- Detection of plaster and tile delaminations
- Location of mounting parts behind plaster
- Characterisation of masonry structure behind plaster
- Location of empty joints
- Detection of enhanced moisture
- Location of delaminations of strengthening materials

A relatively new approach of active thermography is the *pulse phase thermography* (PPT). The stored data received during the IT is analysed in the frequency domain via Fast Fourier Transformation of the transient curve of each pixel in a series of thermal contrast images. This leads to changes in amplitude or phase of the corresponding images. The main advantage of PPT lies in the phase images, which are reported to be less influenced by surface infrared and optical characteristics. That also means less sensitivity to non-uniform heating compared with the thermal contrast images. Thus, the possibility of using the information from the phase images will be considered.
Radar measurements are nowadays widely used for non-destructive testing of masonry structures. Nevertheless mainly profiles are measured and interpretation is done by examination of raw data only. But radar is a much more powerful tool. Especially when data are recorded along a regular and dense two-dimensional (2D) grid on the surface of the structure under test, advanced interpretation tools can provide detailed information on the subsurface build-in parts and inhomogeneities like metallic inclusions (e. g. anchors), voids and the brick structure. For higher accuracy of measurement positioning a 2D scanner system was developed at BAM, where the radar antennas are mounted and continuous profiling can be done on the covered area in one step automatically.
For data interpretation a highly sophisticated reconstruction technique called 3D FT-SAFT (three-dimensional Fourier Transformation Synthetic Aperture Focusing Technique) can be applied. The results of the reconstructions give a much clearer and focused picture of hidden structures. By covering the area of interest twice with different polarization of the electric field of the electromagnetic waves, linear structures in any direction can be resolved. The resulting three-dimensional (3D) data cannot only be visualized by different slices. 3D pictures and 3D videos improve the understanding of the shape of inclusions especially for complicated subsurface situations.
Impulse radar is based on the emission, reflection/transmission and detection of very short electromagnetic impulses by an antenna system. Reflection of the emitted impulses occurs at interfaces between materials with different permittivity or conductivity, e.g., at the surface of the structure under investigation (interface air/building material), at interfaces of layered materials, at voids, inclusions and other inhomogeneities inside the material and at the backside of the structure (depending on the thickness). The propagation velocity and the signal penetration depend on the electric and dielectric properties of the materials. Since these properties are strongly related with the moisture content, radar can also be used for moisture detection and rough quantification.
In the past, this technique has been applied successfully to the following testing problems:

- Determination of thickness of walls and layers
- Location of voids
- Location of metallic bars and anchors
- Location of delaminations of external leaves
- Detection of masonry inhomogeneities (e.g., variation of masonry texture, repair interventions,...)

The *Acoustic Energy Absorption Diagnostic Device* (ACEADD), realized at the Institute of Acoustics

(IA - C.N.R), will provide important information with *non invasive* and *non destructive* investigations about the degradation state of heterogeneous structures such as mural paintings an mortars, employing *no-contact geometry*; it is based on the acoustic energy absorption phenomena.
This tool provides objective data for the:
- Diagnosis of the degree of deterioration of mural paintings;
- Time evolution monitoring of detachments by means of periodic exams, integrated by correlation to environmental data.
Partners involved = BAM, ICVBC (IA)

The *X-Ray Diffraction Technique* is based in the measurement of the distances between crystallographic plans in some phases of a steel element. These microscopic distances are related with the engineering strains by means of well known mathematical relations. This Non Destructive Test has a Standard for the measurements of the Residual Stresses in steels. There exist standard portable equipments in the market for its application. X-Ray Diffraction Technique is the one of the Non Destructive Test for the measurements of the on site stresses in steels**.**
The technique will be applied where there exists steel like structural material (rings, steel bars across a nave or dome). Even more, X-Ray Diffraction technique will allows the checking of the stresses in metallic materials (structural frames) introduced in the restoration processes like consolidation elements. The tests will be focused in order to check the technique for low strength steels and in setting up an easy procedure for the on site measurements.
Partner involved = EPV/EHU

Fluctuations and Structural diagnostic of the structure foundation in case of biodegrading soil
The FOS fiber optic system in Gdansk will be used for long term monitoring of the settlement of foundation (IPPT, SMARTEC) accompanied by analysis of chemical composition of underground water to study biodegradation of the foundations.
Several monitoring campaigns are planned for:
-monitoring of the pore water pressure changes (e.g. by extensiometers –partly and fully saturated zone) depending on weather and water table oscillations and its connection to the moisture of foundation and subsoil;
- long term monitoring of the water table fluctuations;
- monitoring of moisture content of foundations and its subsoil (eg. TDR sensors and/or sampling plus oven-drying) in the dependency on matric suction changes and water level fluctuations – influence of environmental seasonality [Task 6.4]
Also labo ratory investigations of subsoil behaviour in the terms of moisture content vs. matrix suction (estimation of Soil Water Characteristic Curve) and long term behaviour: (e.g. investigation of creep, influence of moisture changes on the subsoil structure and its compressibility) will be performed (ITAM, IPPT). Historical data from piezometric measurements of water table and from geodetic survey of pillars subsidence (GEOT EST) will also be introduced into MachPlatform Database. All the results will be correlated and fed into 3D model of St. John for validation and structural damage identification. Structural diagnosis of the St Jacob test site in Leuven (KUL) will include the influence of foundations and underground on the structural behaviour and results on this test case will assure validation and effective use of techniques in the Common Monumental test case of Ortigia (UNROMA1).

Partner involved = IPPT, ITAM, SMARTEC, KUL, UNROMA1.

Task 6.3 Non-structural diagnostic and materials decay [28 mm]

Determinations of on site chemical, physical, biological, mechanical and environmental parameters influencing mortar-bricks, stones, timber and wall paintings will be made. Environmental factors such as rain, wind, temperature, humidity, chemical composition of soluble and insoluble pollutants will be

determined using the WSN and the new chemical NDT methodologies. The material decay will be described (according to a common terminology), mapped and its development in time monitored. All the information, collected during the different sampling campaigns, will be inserted in the relational data base of the MACH Platform.

- *On site chemical and biological determinations*
- Water soluble compounds
- Organic solvent soluble compounds
- Salt content
- Insoluble compound*s* and minerals
- Identification of biological patinas
- Photosynthtic pigments

The moisture and salt content distribution in the walls will be measured with non destructive and/or little destructive techniques. All the information, collected during the different sampling campaigns will be preliminarly inserted in the Monument Damage Diagnostic System (MDDS) and then in the MACH Pla tform.
Partners involved = TNO

The specific work to be performed in this subtask considers three main innovative topics (UPV/EHU):
a.- The use of NDT instrumentation, not used till now for in-situ analysis to systematically analyse the composition, both elemental and molecular, of the bulk and degraded compounds of the original mineral phases present in the functional and decorative elements of the monument. This instrumentation uses mainly portable Raman microprobe spectroscopy and micro-XRF spectrometry and is quite well suited for insoluble compound identification.
b.- The use of new NDT methods to extract, either polar and non-polar compounds present in the surface and pores of materials as a consequence of environmental impacts. This extraction procedure does not alter the composition of the stones or plasters and will allow us to determine the chemical componentes at low concentration, by using chromatographic techniques (they are not detectable by the spectroscopic techniques due to its low concentrations), together with their decayed compounds formed after its reaction with the bulk of the materials. These NDT methods are directed to the water soluble and organic soluble compounds
The *chemical method* is based in the application of a “poultice” made of: (a) an special but commercial anion exchanger in the form of EDTA, (b) a diluted solution of the same composition of that used to condition the anion exchanger, at $6<pH<8$ and (c) a non-reactive non soluble polar binder. This “material is set for 24 hours on the wall or the stone that is going to be analysed for soluble salts. After that time, the “poultice” is removed and the anion exchanger material is separated from other materials, then the trapped ions are eluted from the exchanger and finally they are analysed by Ion Chromatography (anions) and by ICP/MS (elements).
c.- The new NDT techniques developed in task 5.2 will be applied for the on site biological monitoring in monuments. The method is based on *Image Analysis of Spectroradiometry* and allows quantifying phototrophs and other organisms of the biocenosis of any subaerial surface.

As part of the adaptation of micro organisms to growth on surfaces, biofilms are capable of binding organic and inorganic materials and thus form a special and unique microhabitat. In fact, biofilms can act as sinks and organic and inorganic contaminants can be concentrated in the surface of monuments colonized by these organisms. However little is known about the significance and interaction of biofilm aterials to adsorb contaminants and to what extent they contribute to the degradation in moderate polluted systems as cities, where most of the historical buildings in Europe are located.
Micro-environmental determinations of insoluble and water or organic solvent soluble compounds and ecophysiological characterization of the biofilm (and the seasonality effect on its [Task 6.4]) could be crucial to assess a comparable diagnostic of historic buildings in the same or distinct climatic region.

Several kinds of organisms with different metabolic activities contribute to monument weathering processes. These vary among Climatic Regions and can be exacerbated by local environmental factors. Remote non destructive detection of phototrophs on monuments by *fluorescence techniques* will be used to evaluate the physiological status as a function of the environmental constraints.
A complementary non destructive portable technique is *Image Analysis of Spectroradiometry*. Differential patterns of pigment distribution and composition resulted in important differences in reflectance of surface optical properties. Due to differences in surface reflectance of weathering processes caused by biodeteriogens on stone monuments this technique will be used to quantify phototrophs and secondarily other organisms of the microbiocenos of a material. The validation of this technique will performed on one hand by comparison with fluorescence parameters, HPLC analysis and in the other, and with functional biodiversity of microbial community of biofilms, using Biolog EcoPlates.
Partners involved: EPV/EHU.

- On site physical and environmental determinations
This will include measurements of temperature and humidity at every monumental test sites while more measurements will be performed in Common monumental Test site in Ortigia (wind, rain and solar impact). NDT technology will be applied to analyse particulate matter, by using SEM/EDS coupled to microRaman (in the same instrument), with the aim of identifying mineral phases in the atmosphere around the monument and passive sampling will be applied by using specific membranes to selectively trap acid gases, organic compounds, volatile metal salts, etc. Acid gases, organic volatiles and particulate matter are trapped depending on the characteristics of the membranes. Appropriate membranes will be selected at the beginning of the projec to be compatible with the parameters that are going to be defined.
Appropriate technologies for on site water uptake (Contact Sponge) and moisture content monitoring in architectural fabrick will be used.
Using the dedicated sensor's modules of the *WSN* the following parameters will be monitored:
- *Gas (NO_2 – CO_2 – O_3 – NH_3)*
- *Temperature and humidity (exterior and interior)*
- *Wind parameters (velocity – direction)*
- *Ra in impact (experimental)*
- *Solar irradiance*

Partners involved =UNIROMA1, ICVBC, UPV/EHU, SINT/HTS

The portable *Surface Meter* device will be applied to make measurements of surface parameters and visual properties (3D- surface topography and visual RGB). The technique used in the portable strument will produce a 3D Optical Roughness Image of the tested area in grey scale for the z axis. Value of roughness can be derived for any x-y point together with the RGB chromatic values.
Partners involved = INNOWEP.

- On site mechanical determinations
Improved innovative Microdrilling, Compact Diagnostic Test and Indentation methods (WP 5), will be used for diagnostic determinations of mechanical properties of deteriorated structural materials. The methods combined all together allow to determine changes in elastic and strength properties of materials such as: material hardness, modulus of elasticity, flexural strength, uniaxial compressive strength, indirect tensile strength.
Algorithms for back-analysis of microdrilling and indentation test results for the determination of the strength and elasticity properties of rocks, monumental stones and artificial materials (mortars, bricks, concretes etc) developed in the frame of DIAS Project will be used for reliable estimation of parameters for numerical simulation tools and evaluation of on-site monitoring results. In this task these algorithms will be applied for the estimation of the mechanical properties and damage of any material in the

selected benchmark monuments by employing the Microdrilling, Compact Diagnostic and Indentation tools. The data of environmental and structural loads and data recorded with different methods (radar, ultrasonic, active thermography, wireless sensors, mechanical properties) etc. will be used in WP 8. For this purpose concepts for efficient mathematical fusion of data (hard- and software) will be developed. The databank, with the strength and elasticity of tested rock or artificial materials, developed in the frame of DIAS will be upgraded and inserted in the Mach Platform.
Partners involved: SINT, IPPT, TUC.

Task 6.4 Value of seasonality for on site monitoring determination

It is focused at analysis of spatial-te mporal trends of the environmental loads and factors and their impact on monument as a whole. Inner and outer walls of structural elements and surfaces of decorative materials are subjected to seasonal variations of climate and climate driven conditions. Environmental factors like moisture, temperature, solar radiation, wind loads, water table level and rain and ground water biochemical aggressiveness deteriorate cultural heritage materials both through mechanical (e.g. thermal stresses, erosion, dust particles) and bio-chemical impact (e.g. biodeterioration and products of chemical reactions of soluble metals and anionic complexes like chlorides, nitrates). Mechanical, environmental and surface analysis determinations made at Common Monumental and Benchmark test sites will be used to analyse seasonality of the environmental loads and factors as a crucial element in behaviour trend analysis,.
Partners involved: ICVBC, UPV/EHU, ITAM, IPPT, TT

Technologies applied

For structural determinations (including foundation):
- Piezometers
- Strain gauges
- Ultrasonic Pulse velocity
- XRD Technique
- Chemical composition changes of the ground water
- Wireless Sensor Network and Fibre Optics sensors
- Accelerometers and dynamic structural response (including ground transfer function)
- Laboratory calibration tests

For the investigation of non structural materials of building elements:
- Automatic radar scanner
- Microdrilling
- Hole drilling
- Compact Diagnostic Test
- Indentation
- Back-analysis of experimental results
- Sonic and ultrasonic investigations(physical property: acoustic impedance)
- Active thermography (pulse-phase thermography) for the investigation of defects and inhomogeneities in the near surface region
- Microwave methods (physical property: permittivity)
- Time domain reflectometry (TDR) (physical property: permittivity)
- Infrared-Reflectometry (infrared absorption of water)
- Nuclear magnetic resonance (NMR) (spin resonance of hydrogen nucleus)
- Ultrasound Fibre sensors (absorption in dye)

For analysis of environmental contaminants and their products:
- Coupled SEM/EDS-microRaman to perform on them a microanalysis to identify non soluble inorganic mineral phases extracted from the degraded grains on the surfaces or pore deposits.
- Ion Chromatography to quantify anions and cations in a microsample (100-500 mg) of heritage

materials.

- Portable Raman Spectrometer and Portable micro X ray Fluoresce Spectrometer for in situ analysis of the particular solid species
- GC-MS to identify and quantify organic compounds soluble in organic solvents.
- FT-IR analysis of the solid residue obtained after evaporation of the solvent .
- Portable Fluorimeter for the investigation of growth and activity of Phototrophs
- Spectroradiometry and HPL Chromatography with photodiode-array detector to quantify organisms and photosynthetic pigments and antioxidants.

Innovation

Implementation at benchmark sites of innovative portable diagnostic tools and stationary Wireless Sensor Network for continuous monitoring system. Only non-destructive and minor-destructive methods (NDT & MDT) will be used.

Partner involved : ALL,

Milestones & Deliverables

ML6.1 - Diagnosis and Monitoring protocols
ML6.2 - Installation of the FOS and wireless monitoring system (WSN) at the benchmark test sites
ML6.3 - Data elaboration and integration

D6.1 – Monitoring Protocols
D6.2 – Data Base
D6.3 – Seasonality charts for environmental dependent parameters

Workpackage number	**WP7**	**Start date or starting event:**					**Month 6**
Workpackage title	**Standardisation of Techniques and Methods**						
Activity type[1]	**RTD**						
Participant n°	**ICVBC**	**UPV/ EHU**	**KUL**	**SINT**	**SMARTEC**	**INNOWEP**	**UPC**	**UNRO MA1**
Person-months per participant	**0.5**	**3.5**	**0.5**	**1**	**1**	**0.5**	**0.5**	**0.5**
Participant n°	**ITAM**	**IPPT**	**BAM**	**TNO**	**UMINHO**	**TT**	**Total**	
Person-months per participant	**0.5**	**0.5**	**1**	**0.5**	**0.5**	**2**	**13**	

Objectives

The redaction of recommendations and guidelines for the use of the innovative techniques and methods, developed and/or verified throughout the MACH, for diagnosis and monitoring a monument as a "whole".

Description of work

In previous Research Projects the European research groups have developed a lot of procedures for the characterization of the Cultural Heritage constructions. Most of these techniques are not transmitted like a document that allows its ample diffusion. On the other hand, the Cultural Heritage needs to have a set of techniques and methods for its preventive characterization. They have to be useful, verified and Non Destructives. Observing the annexed documents (ANNEX 2), many of these techniques and methods have their origin in other fields of Science (Medicine, Civil engineering, etc.). In order to be applied in the Cultural Heritage sector the procedures of these methods and techniques must be adapted for this new use.
In this WP the recommendations and guidelines for the application of the techniques and methods developed (WP5) and applied for on site diagnosis and monitoring (WP6) will be elaborate. Furthermore, in those cases in which the guidelines contribute to covering an important lack of knowledge, they will be proposed for standardisation to official bodies (CEN, RILEM).
The following are some techniques that, after their on site validation on the basis of the aim of the project, will be discussed and the normalised procedure for their application will be draft.

Task 7.1 Non Structural characterisation - [7 mm]

Name of the Technique: **Active thermography**
Parameter (s) to be measured: On site delaminations, voids, structure behind plaster
Material (s) to be applied: wallpaintings, plaster
Benefits, Impacts or Degree of Innovation
The main innovation of the technique is to get quantitative information about the investigated structure, e. g. the depth and size of the detected delaminations, and to suppress the influence of surface inhomogeneities and inhomogeneous heating. A further step of innovation will be the fusion of data from active thermography to data recorded with other methods from the same structure

Name of the Technique: **Radar for structural investigation of historic masonry**
Parameter (s) to be measured: Position and depth of inclusions and voids, thickness of walls and layers
Material (s) to be applied: Plaster, brick, stone
Benefits, Impacts or Degree of Innovation
The main innovation of this technique is to get a 3D presentation of the internal structure of the elements under investigation. If there is a high absorption inside the material, the reflection data have to be combined with reconstructions of transmission measurements, from which the travel times were analysed to obtain information about the velocity distribution inside the structure. A further innovation is the presentation of fused data sets from complementary methods, e. g. radar and sonics/ultrasonics.

Name of the Technique: **Surface Pattern Analysis**
Parameter (s) to be measured: Surface topography (roughness) and colour
Material (s) to be applied: Any materials present on a monument
*Proposer:*INNOWEP
Benefits, Impacts or Degree of Innovation
The main innovation of this technique is to get a 3D numerical presentation of the superficial pattern of the material under investigation.

Name of the Technique: : **Determination of moisture and salt distribution in masonry**
Parameter (s) to be measured: Quantitative moisture content, quantitative salt content, moisture and salt distribution
Material (s) to be applied: Mortar, plaster, brick, stone

*Proposer:*BAM
Benefits, Impacts or Degree of Innovation
For getting a fast survey of a large area (e. g. part of the wall), radar investigations can be performed in reflection or transmission mode. Time domain reflectrometry (TDR) and application of microwave methods at different fre quencies and comparison of phase and amplitude give qualitative information about salt content.

Name of the Technique: **Non-destructive extraction of soluble salts by ion exchange**
Parameter (s) to be measured: Cations and Anions belonging to the soluble salts
Material (s) to be applied: Ion exchangers supported in a non-reactive poultice
Proposer: UPV/EHU (Environmental Analytical Chemistry)
Benefits, Impacts or Degree of Innovation
This methodology, based on the new "poultice", is intended to be an alternative to the destructive current method of soluble salt extraction (Normal 16/83)
The technique has not been used or employed till now, and we will proceed for their standardisation following the rules of the Method Validation Protocols. This work will be managed by one member of the research team that is the Spanish representative of the TRAINMIC programme for chemical measurements of the Joint Research Centre IRMM (Geel, Belgium) and he is an expert in standardisation protocols, both for techniques and methods with a chemical basis.
Under his expertise all the techniques and methods based in chemical measurements, and worked in WP5 and WP6, will be also validated in order to check if there are possibilities to their adoption as future standard procedure.
If the technique demonstrates its robustness, the innovative extraction material will be patented because a standard procedure can not be used if appropriate materials are not available in the market

Name of Technique: **Non destructive techniques to estimate biodeteriogens**
Parameter(s) to be measured: On site biological stresses with Chlorophyll Fluorescence, Spectroradiometry and Biolog Physiological Profiles
Material(s) to be applied: Masonry materials
Proposer: UPV/EHU (Plant Biology and Ecology)
Benefits, Impacts or Degree of Innovation
Irrespectively of the step to be worked during the whole standarization procedure, well accepted protocols for measuring uncertainties and verifying trueness will always be applied.

Task 7.2 Structural characterisation – [7 mm]

Name of the Technique: **Hole Drilling Technique**
Parameter (s) to be measured: On site stresses
Material (s) to be applied: Stone Masonry, Brick and Mortar
Proposers: SINT and UPV/EHU (Faculty of Architecture)
Benefits, Impacts or Degree of Innovation
Related with the On Site Stresses Measurements in Cultural Heritage the standardisation of the Hole Drilling Technique is the most innovative contribution for MACH. This technique will be the only Minor Destructive Technique to solve the problem. The scientists of Basque Country University (UPV) work since 1992 in order to set up the Hole Drilling Technique (named Donostia Method in several papers). Three Research Projects funded by Spanish Government (R&D National Programme) have been dedicated to check all the aspects involved with the technique. Likewise they were invited by GEOCISA for participate in ONSITEFORMASONRY (FP5 Project). They have analysed the stresses in the Altes Museum of Berlin with other European groups. The Technique is based in the Standard ASTM 837 95 for Residual Stresses measurements in steels. The procedure there described is not able to be applied in Cultural Heritage Constructions because the dimensions, the size of the strain gages

and the specific tools are very different. Thus the Hole Drilling is a very proven technique not yet standardised in Cultural Heritage applications. SINT Partner works in the same direction since some years. The synergy between both partners (one research partner and one SME partner) assures the success of this specific objective.

Name of the Technique: **X-Ray Diffraction Technique**
Parameter (s) to be measured: On site stresses (Before of after the Restoration Process)
Material (s) to be applied: Steel elements
Proposer: UPV/EHU (Faculty of Architecture)
Benefits, Impacts or Degree of Innovation
By the moment there is not a technique for that in Cultural Heritage Constructions. The adaptation of this technique in the constructions of the Cultural Heritage will be the first time that is made in the international scientific community. After revision of the proceedings and index of the most important Conferences and scientific Journal (more than 20.000 papers revised) no paper about this technique in Cultural Heritage applications has been detected. Nevertheless the method has been proven and diffused in a exhaustive way in some scientific fields.

Name of the Technique: **Wireless Sensor Network**
Parameter (s) to be measured: Several structural and environmental
Material (s) to be applied: on a monument as a whole
Proposer: ICVBC - SINT
Benefits, Impacts or Degree of Innovation
The main innovation of this technique is to propose a low cost integrated network of sensors able to monitoring several structural and environmental parameters and transmit the data to a remote unit.

Milestone & Deliverables

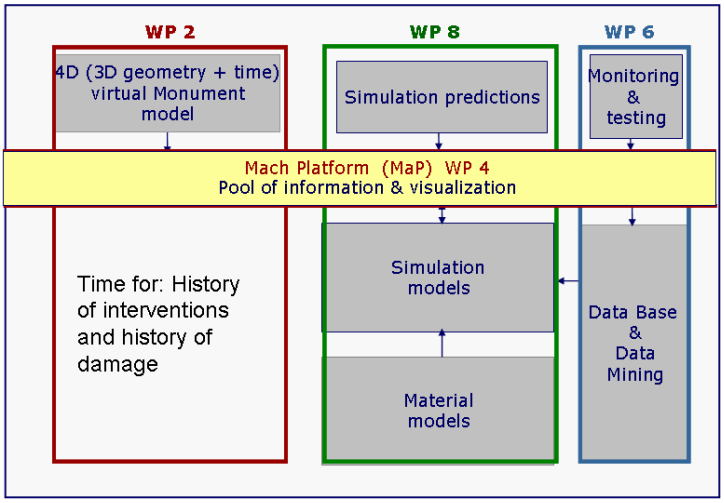
ML7 – On site validation of new and improved methods and technologies for on site diagnosis

D 7 - Guidelines and proposals of Standardizations for the validated techniques and methods

Workpackage number	**8**	**Start date or starting event:**			**Month 12**
Workpackage title	**"Analytical and numerical methods: Probabilistic Risk Assessment"**				
Activity type[1]	**RTD**			**Total**	**52.5**
Participant n°	ICVBC	UPV/EHV	KUL	TUC	SMARTEC	INNOWEP
Person-months per participant	3	6	7	15.5	2	2
Participant n°	UPC	UROMA1	IPPT	BAM	TNO	UMINHO
Person-months per participant	2	4	1	2	1	5

Objectives:

Numerical simulation models based on the Finite Element Method (FEM), Finite Differences Method (FDM), Boundary Element Method (BEM), Distinct Element Method (DEM) etc. are essential tools for assisting the selection of the best design of the intervention (maintenance) method of a monument. A numerical model allows the engineer to test various design scenarios before intervention commences and to assess with respect to economy and stability different alternative designs. Thus, the monument to be maintained at the best possible condition may be placed in a "virtual space" (i.e. the computer) prior to making any intervention in reality or prior to some environmental or other disturbance that may affect it in the future.
We envisage in this project the creation of the **'virtual monument'** that is a **quantitative-visualization tool** containing all the structural and non-structural key elements affecting the performance of the monument itself. This 'virtual monument model' will be calibrated with in situ monitoring measurements transferred from WP6 through the common MACH Platform. The calibrated model(s) will be used for the prediction of short, medium and long-term behaviour of the monumental structure at all scales for the application of the best maintenance or protection strategy. For that purpose special constitutive models of damageable materials in chemomechanical environments are needed, so a "Model Advisor" will be created to help the designers. All numerical models and the "Model Advisor" will be uploaded in the Mach's Platform (MaP) of WP4 and will be used later in WP9 for the expert Decision Support Tool (DST).
The requirements needed for the final DST in the WP9 are coming from the information gathered in the previous WP's, such as the available 3D geometrical model (WP2), the data coming from the monitoring programme for non-structural and structural parameters (WP6). These data are the input for the continuum Finite Element Models (FEM) or the Discrete Element Models (DEM) that have to result in an objective appraisal of the state the structure is in. The same serves as basis for the risk assessment in this WP. Finally, this has to be included into the Decision Support Tool (DST). This interlink of WP's with the Mach Platform (MaP) is illustrated in the figure below.



Schematic diagram illustrating the connection of three WP's with the MaP (MACH Platform).

Description of work

The 'wholistic' analysis of the mechanical behaviour of ancient structures at all scales (material grain scale, structural discretization unit (element) scale, individual structure scale (i.e. beam, column etc.) and whole monument structure scale) subjected to any form of mechanical or environmental load, is an essential engineering component of projects concerning the preservation of the architectural heritage. This task is very complicated due to the following facts:
(a) many materials have been used in the past and in various types of structures (i.e. vaults, pillars, arches, buttresses, masonry walls etc) in the monument;

(b) the properties of the old and possibly new stone elements are heterogeneous;
(c) the materials are subjected to various types and levels of damage due to mechanical loads (structural factors) and environmental attacks involving diffusion processes (non-structural factors).
Up-to-now there is no 'wholistic analysis' of monuments. Only a plethora of models that are very far away from reality and practicability are proposed because they do not attack the problem at hand in an interdisciplinary and cost as well time-effective manner for decision making. Weathering mechanisms are not adequately investigated and only in a qualitative manner, the constitutive models proposed do not take into account the coupling of various mechanisms occurring in practice such as coupled mass balance, stress balance laws, energy conservation and entropy laws (for example freezing and thawing in the presence of cyclic mechanical loads applied on the boundary, etc.).
Furthermore, because of the large values of empirical safety factors used in mechanical design, rationalizing them with extreme-value based statistical mechanics in a stochastic modeling approach is an enormously promising prospect. Hence monitoring in combination with a calibrated analytical and mathematical-numerical models are needed for the answers to the questions below:

1. What is the initial damage level (effect) & which are the causes? Understanding the mechanisms of damage.
2. How the residual strength and elasticity of the monument depends on the degree of its damage?
3. Which is the acceptable damage level for the estimated operating loads acting on the monument? Risk analysis & Risk estimation.
4. How much time it takes for the damage to grow up-to the critical damage state? Short-term & long-term behavior of monument.
5. Which level of damage is acceptable for the safe operation of the monument under given environmental and loading conditions?

Some hazards are more likely in some areas within the European country compared to others. Therefore, the selected case studies worked out by the different partners involved will focus both on:

- The hazards encountered in specific areas within sub-teams, like the vulnerability of ancient structures in seismic prone areas (Italy, Portugal)
- The hazards encountered in general within all partners of the consortium (differential settlements due to foundation problems, elevated stress levels into degrading masonry).

This task is a key task in the objective towards decision making, both for the structural and non-structural analyses. Analyzing the risk involves the appropriate knowledge of several key issues:

- The behavior of the structure: this could be both the structural behavior and degradation process. Since methods use models, this involves structural models and degradation models;
- These models have to be fed by input parameters: loading (load effects) and resistance (resistance effects);
- This involves material parameters (structural and non-structural);
- To enable the risk assessment, an objective procedure has to be put forward. Since a lot of uncertainties are involved, related to loading, resistance, geometry, model, etc. a rational treatment of uncertainties is preferred. Therefore, a stochastic procedure will be employed.
- Criteria have to be also formulated which the overall performance of the structure have to meet.

Some of the **innovative aspects** of this WP8 – not yet developed in the Cultural Heritage sector - are the following:

1. Effort will be made to consider in the simulation models all the relevant constitutive properties of the materials composing a monumental structure from the grain scale (10^{-6} m) to the structural scale (10^{1}-10^{2} m).
2. The damage imparted on the structural members due to environmental and mechanical loads will be evaluated with regards to its origin, quantified and considered quantitatively in the simulations based

on fundamental concepts of **Damage Mechanics**[1]. That is why will invoke the quantitative constitutive description of "damageable materials" into the simulation tools.

3. A **"Model Advisor"** will be developed and uploaded in Mach's Platform (WP4) for a user friendly suggestion of the type of simulation tool and constitutive description appropriate for a specific application.
4. Transfer of digitized monument developed in WP2 directly into the FEM or DEM model via the web-platform (MaP).
5. Consideration of the foundation of the monument within a "wholistic approach".
6. The **statistical aspect** of loads, material properties and damage will be also considered in the frame of Risk Analysis
7. All numerical simulating tools will be integrated into the MACH Platform and will be used later in WP9 for the elaborate the creation of the **expert system** of Decision Support Tool (DST).

The following two complementary Tasks are foreseen:

Task 8.1 Deduction of the monument state by means of analytical-empirical methods (classical approach)) and numerical tools (modern approach)

a - Formulation / application of analytical methods for analysis of the state of a monument

b- Use of the discretized 3D models for the distinct and finite element analysis of the selected monuments;

Task 8.2: Creation of a Risk Assessment Model

a - Definition of the parameters to be mapped in the numerical model

b - Identification of the Constitutive Laws (material behavior) for the different materials and elements.

Task 8.1 Deduction of the monument state by means of analytical-empirical methods (classical approach) and numerical tools (modern approach) – [33 mm]

a - Formulation / application of analytical methods for analysis of the state of a monument (KUL & UPC)

In the frame of a hierarchical approach,, before going in to depth on numerical models, attention is paid to the formulation and application of **analytical** methods. It is important not only to deal with numerical, say FEM//DEM models. In a subsequent step in WP9, also use will be made of analytical (simple) models for the DST. It will not (always-certainly not for all monuments) be possible to include complex and expensive analysis tools – which is the reason for which low-cost universal wireless network sensors are designed for in WP5. Several analytical methods have been established related to the diagnosis, safety and risk assessment of the structure. These methods are of prior importance since these provide a close relation with the (structural/non-structural) insight we have into the structural behavior of the monument as a whole on the one hand, and can be linked with the information obtained from monitoring on the other hand.

This is clarified by means of an example. The ancient constructors used simple proportions and classical concepts of graphical analytical methods to build their arched structures. Following the theories of Jackues Heyman[2] and others (initially mentioned by Leonardo Da Vinci) the safety of a masonry arch depends on the position of the line of thrust. "*When a thrust line can be found that is in equilibrium with the external forces and lays within the physical cross section of the arch, the arch is safe*" (Heyman, 1999). The assessment thus requires the knowledge of the geometry of the arch analyzed. This methodology can be extended towards vaults or even to domes. In these cases however, the analysis in fact is more complex and the thrust line methodology would result only in an estimate. However, this ancient "technology" can solve actual problems and certainly offers a great insight into the structural thinking at the time of construction and for that reason is indisputably of interest when studying the Monument as a Whole. As mentioned before, graphostatics is

[1] As was developed by Kachanov, Krajcinovic and Lemaitre.

[2] Chapter 3 of J. Heyman, *The science of structural engineering*, Imperial College Press, 1999. For a deeper analysis of masonry, see J. Heyman, *The stone skeleton*, Cambridge University Press, 1995 (paperback 1997, 1999).

useful in the analysis of arcs, vaults, columns and or even domes. However, for these type of structures numerical tools such as FEM are more versatile and can take into account more complex geometries, and (combined) loading.
To derive the structural states of historical masonry structures, an appropriate and unbiased model is required. It is clear that, the better the model is able to predict the real structural behavior, the better the resulting risk assessment will be in the end.

With regard to non-structural elements of the monument, emphasis will be set in the identification of adequate Chemical and Biological Parameters, obtained from WP6, to be taken into account in order to define the model of Risk Assessment, as well as in the validation process of the chemical and biological parts (non-structural) of such model.

One of the actions will identify the key parameters in the soil, the superficial and groundwater in those soils, the indoor air and the outdoor air compartments. The way they affect to the functional and decorative elements of the monument will de standardized. Moreover, the risks associated to the non actuation on a given pathology will be assessed trying to identify the possible damage in the medium-long term.

In another action, the most vulnerable compounds present in the original materials will be identified, i.e., those susceptible to be attacked by the environmental parameters, previously identified as the most dangerous for the different functional and decorative elements of the monument.
Adequate Biological Parameters obtained from WP6 will be taken into account to obtain the model of Risk Assessment. Moreover, the risks associated to the role of decayed compounds identified in Task 6.3 will be assessed considering three scenarios (a) leaving those decayed compounds as such in the surfaces, (b) cleaning them by conventional procedures and (c) cleaning them by the most adequate procedure proposed by MACH expertise.
In this Task we will develop parts of the model that will be included in the Decision Supporting Tool for the diagnosis of damage caused by phototrophs , residual life and maintenance strategy of monuments (related to WP9)
- Due to the importance of ecophysiological changes in the biota as a function of microenvironmental conditions, climate and substrate, the correlations among parameters tested by all groups can be very important to identify and understand critical periods and local environmental conditions for diagnosis of damage.
- The information acquired will allow to implement a decision tool for residual risk evaluation and the weak points to prevent further damage on monuments or main agents causing or contributing to the decay over the residual life.
- Optimal and alternative strategies of biocontrol, when needed, as a function of local biofilm (structural and functional biodiversity), climate, season and materials of the substrate. The decision tools should consider the appropriate methods in terms of avoiding present or future damage, interaction with other undesirable agents, as contaminants, effectiveness, costs, etc.

We propose to afford a parallel action to help in the construction of the model from the chemical point of view. We will start from the data collected by the NDT/MDT technologies and methods, previously used and validated, as inputs for two simulating tools in order to evaluate the cause/effects of the damage:

[3] Itasca Consulting Group Inc. (2003), *3 Dimensional Distinct Element Code (3DEC)*

[4] Experience has already been gathered in this topic. This has been performed in close collaboration with Pierre Smars, a former researcher at our university who now is associate professor at the Yuntech University of Taiwan (email: smars@yuntech.edu.tw). His Ph. D. thesis (promoter: Koenraad Van Balen, was very much related to this subject, entitled: “Etudes sur la stabilité des arcs et voûtes: Confrontation des méthodes de l'analyse limite aux voûtes gothique en Brabant, Ph.D., Pierre Smars (2000)). During his Ph.D. he worked out a software tool to calculate thrust-lines in arches. The latter has been coupled with a reliability based algorithm to assess the safety of an arch. (Ph.D. Luc Schueremans, “Probabilistic evaluation of structural unreinforced masonry”, KULeuven, 2001).

- The MEDUSA software to simulate chemical reactions. Starting from the knowledge of the original materials and the degradation products, we will try to define which kind of reactions could happen to produce the detected degraded compounds from the original ones
- The UNSCRAMBLER software to perform chemo metrical computations. Cluster Analysis, Correlation Analysis and Principal Component Analysis will be the three chemo metrical tools to define, for the different parts of the monument that have been monitored, which compounds are showing similar behaviours and thus which are related through a cause or a effect or by both
- The mixing of the two predictions will allow us to formulate the cause (even to identify the sources of damage) that has promoted a given effect, always due to chemical reactions

Also, related to the Maintenance strategy from the knowledge of the chemical reactions causing effects, we propose to afford a new action. In this we will start from the knowledge of the sources of damage and the mechanism of degradations. This is the required information to take measure in order to:

- Prevent a longer life for the still non affected materials by protecting them in a given way (not a standard for all the materials but a dedicated treatment for given materials with similar chemical compositions)
- Set "barriers" in order to stop the impacts caused by the environmental sources acting, from the chemical point of view, on the monument
- Select the most adequate cleaning procedure for a given material
- Select the most adequate consolidation procedure, paying attention to material compatibility among the original ones and the new ones introduced by the treatment.

These treatments probably will be different for the functional and decorative elements because some will be mortars, with or without wall painting, and others stones as such. All this information will help the works in WP9 and are important parts of the web driven platform developed in WP4

b - Use of the discretized 3D models for the distinct and finite element analysis of the selected monuments (TUC, ICVBC-ISTI, IPPT, KUL, UMINHO)

To perform an overall analysis, an appropriate representation of the real structure is indispensable. This is true on different scales: on micro-, meso- or macro-scale. The construction of an overall 3D-model of the structure focuses on the macro-scale and is strongly linked with WP2.1 (construction of the geometrical interactive 3D-models (4D)). The objective is to achieve all steps required to build a 3D-model based on the in site data-acquisition (from 3D-point-cloud to 3D-model of the structure). The latter has to facilitate the building of the discrete structural model needed in the structural analysis. Therefore, several items are looked at in more detail:

- Data-acquisition of 3D-point clouds, 3D scanning, (WP2);
- (Automatic) construction of lines, surfaces and volumes (and meshing) from 3D-pointcloud (and combined with photo-grammetric survey) – identification of geometry (WP2);
- Image-based reconstruction solutions (WP2);
- Generating correct communication tools for further processing within distinct element ($3DEC^3$) and finite element codes (ex.: NOSA; CALIPOUS and others involved in the project) (WP2);
- Methodology to incorporate and visualize sensor-data from in site measurements during monitoring campaign (WP6).

Based on the available 3D model of the structure (WP2), integrated within the MACH-platform MaP (WP4) the required finite or distinct element model is constructed. This work package covers the requirements to be set to the overall MACH platform (WP4) to ascertain the correct data-transmission needed for the construction of the virtual monument. This subtask covers the establishment of the discrete 3D model for the selected case study (City of Ortegia , Sint-Jackobs, Sant John and Porto cathedral), required for the analysis phase.

A pre-processor will be developed to insert the geometrical 3D scanned model into the discrete 3D-model (CNR-ISTI).

Simple and practical chemomechanical laws of damageable geomaterials developed in **Task 8.2** will be embedded in a next step into the 3D distinct element code 3DEC to determine the vulnerability of the monuments on environmental and climatic attacks (thermal fatigue, mechanical processes e.g. freezing-thawing, salt crystallization, static and dynamic loads etc) (see Fig. 2). This virtual benchmark model will be validated against in situ monitoring measurements (wireless sensors etc) conducted in WP6. One may ask the following question: To what extent is there a relation in between chemomechanical laws related to climatic attacks and the monitoring results coming from a wireless sensor for example that will deal with cracks, settlements, movements in general. The first is related to material properties and decay processes; the second is related to boundary conditions, imposed displacements, etc. How these are going to be merged? The answer to this question is simple, namely: Chemomechanical attacks induce damage in the material based on a certain constitutive law (e.g. **Task 8.2** below), and this damage is reflected with enhanced displacements of the structure and opening of cracks, which are monitored in the monument with the sensors or manifested with degradation of strength and elasticity captured with the non-destructive tools (WP6).

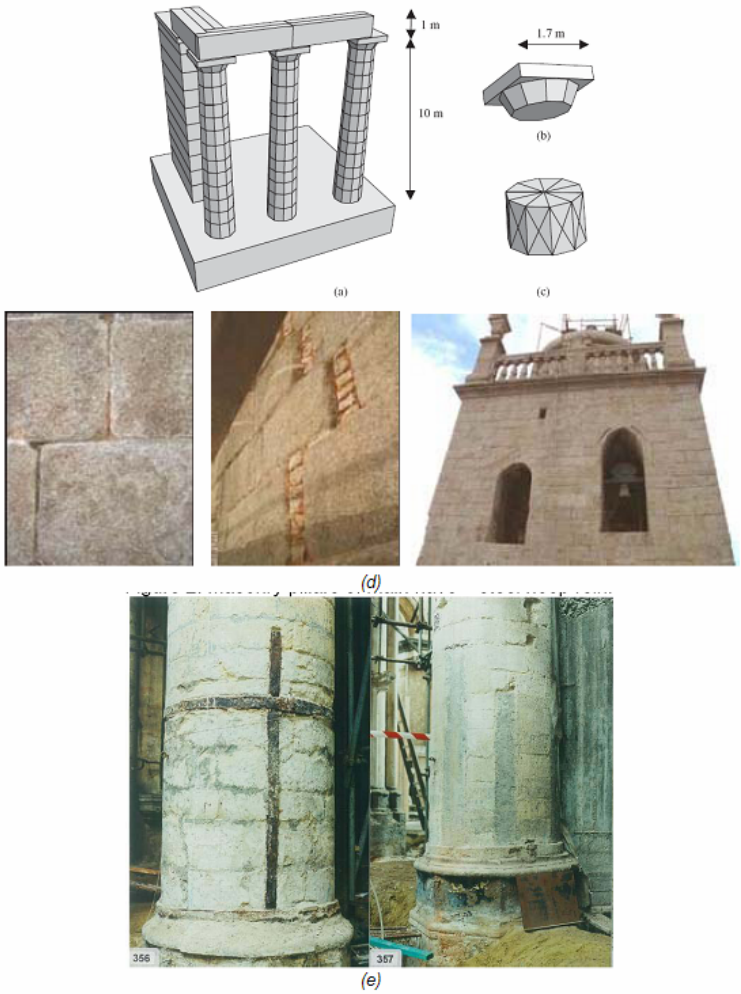
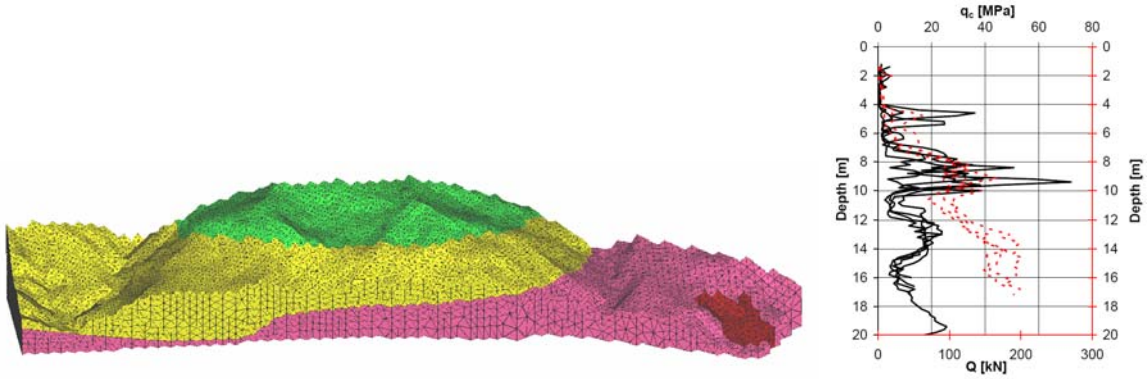


Figure 2. Example of 3-DEC 'virtual ancient masonry structure model'; (a) general view, (b) detail of the capital, (c) discretization of drum block; (d) example of masonry wall structure of cathedral of Porto, and (e) view of strengthened and heterogeneous (replacement of damaged stone elements with new) masonry pillars in St James in Leuven.

In the frame of a wholistic approach the foundation bedrock upon which the monument rests will be also considered in the creation 3D distinct element model (**Fig. 3**).



(a) *(b)*

Figure 3. (a) 3D numerical discretized model of foundation consisting of various geological formations upon which a monumental structure rests; (b) Cone Penetrometer tests – among others - will be exploited to assign geotechnical parameters to the foundation model. Interpolation of geotechnical parameters between measuring points will be done through simulated annealing (i.e. Stochastic – Geostatistical approach).

The other goal of this Subtask is an innovative structural analysis of masonry constructions by means of **continuum numerical analysis**. In particular, four activities will be carried out via the FEM code NOSA developed by the Mechanics of Materials and Structures Laboratory of ISTI: (i) static analysis, (ii) collapse analysis, (iii) dynamical analysis, and (iiii) modelling of strengthening operations.

i) Static analysis. Masonry will be modelled as a non-linear elastic material with zero tensile strength and infinite/bounded compressive strength. The constructions (arches, walls, domes, vaults, etc.) can be modelled in their present situation as well as in the presence of variations of loads and/or boundary conditions. The aim of such modelling is to obtain information about the stress field and cracks distribution, and their evolution when the structure is subjected to variations in loading conditions. The thermo mechanical behaviour of masonry structures in the presence of thermal loads, such as monuments and bridges subjected to thermal variations, can be analysed.
ii)Collapse analysis. A finite element analysis will be conducted by increasing progressively some variable loads until it is no longer possible to find an admissible solution to the equilibrium problem. Collapse load and collapse mechanisms will be determined and the safety of the building will be evaluated.
iii)Dynamical analysis. The dynamic behaviour of masonry constructions in the presence of time-dependent loads, such as urban traffic, wind and earthquakes will be investigated.
iv) Modelling of strengthening operations. The monument will be analysed in its current situation and possible strengthening or restoration operation (fitting of metallic rings, rods, FRP composites, etc.) will be modelled in order to assess their influence on the structural behaviour of the construction. On the basis of the results of such a modelling, the choice of the best restoration intervention will be made, by taking into account several parameters, as costs, architectural impact, static effectiveness, safety improvement, etc.

Also, the following model is included and all will be uploaded in the MACH platform (WP4):

- CALIPOUS (KULeuven, in collaboration with KULeuven/ASRO and Yuntech University, Taiwan)
  A limit analysis of arches and vaults is performed using CALIPOUS, an interactive tool is provided to asses the safety and its relation towards accurate geometrical dimensions;

Simulation of the structural response of the selected case study using advanced software, taking into account local measurements. In particular, UMINHO has available homogenised models and orthotropic constitutive models capable of adequately taking into account the structural masonry behaviour. The information about geometrical and mechanical characterization of materials as input data of the numerical model can be enhanced from the application of new inspection techniques developed in WP6.
Partners involved: ICVBC, UPV/EHU, KUL, TUC, UPC, UNROMA1, IPPT, BAM, TNO, UMINHO

Task 8.2: Creation of a Risk Assessment Model – [19.5 mm]

a - Definition of the parameters to be mapped in the numerical model (TUC, KUL)

Related to the definition of parameters to be taken into account – focus is on several **structural** [STR] and **non-structural** [N-STR] hazards that are be identified threatening the built cultural heritage - a non-exhaustive list may be made, namely:

- Seismic hazard, earthquakes [STR];
- Floods [STR/N-STR];
- Foundation settlements [STR];
- Fire; [STR/N-STR];
- Avalanches; [STR/N-STR];
- High sustained vertical loading on masonry resulting in damage accumulation [STR];
- Humidity-salt crystallization -water freezing [N-STR];
- Air-Pollution [N-STR]
- UV-light [N-STR]

In this WP we will we cover both structural and non-structural loading cases in an integrated manner.

In general, following parameters are to be accounted for:

- Geometry (a);
- Loading (load effect): E;
- Resistance (resistance effect): R;
- Uncertainties: θ.

Related to the different models identified in WP 8.1, a matrix is constructed that lists all parameters required. In addition, a methodology is proposed to fill out the required data in a quantitative way. For that, different sources are identified (all circulating via the MACH platform):

- Geometry, referring to WP 2,
- monitoring and non-destructiv, minor- or semi-destructive testing, referring to WP6;

These data will be store in the database to be worked out, in such a way that it is functioning as a sort of **"Model advisor"** both for the most appropriate simulation tool and for the constitutive model of the material [TUC].

Related to the parameters involved in a probabilistic risk assessment, the parameters mentioned above have to be extended towards a probabilistic model, covering their uncertainties in a rational way. For all parameters identified above, a probabilistic model and model-parameters are put forward if available. In the other case, the needs are identified and in depth research is performed, such as research into a probabilistic material model for masonry compressive strength, based on strength values of brick/stones and mortar.

Parameter identification for input in the 3D distinct element model of heterogeneous and blocky monumental structures (**Fig. 4**) based on (1) upscaling of microdrilling, indentation or ultrasonic test results or other performed in WP6 – with the upscaling procedure to be based on *Continuum Damage Mechanics (CDM) -*

and (2) a combined fuzzy logic - stochastic process such as simulated annealing technique in Geostatistics taking into account inherent variability of material properties due to random and systematic errors and spatial variability.

This procedure is going to be a generic one. It will allow to include randomness in general related to material properties of the monument as a whole, loading to be applied on the monument, its geometry (from the 3D (4D) model and boundary conditions plus time evolution of these parameters as obtained from monitoring results – such as the wireless sensors applied in WP6. For example in Fig. 4, we have 5 different states of decay, with their spatial variability (at the surface). These will be available from the monitoring performed in WP6 and available in digital form within the MACH platform (WP4). These data are included into the DEM or FEM numerical models by mapping the spatial variability of the material parameters into the Gauss points of the discretized virtual monument models.

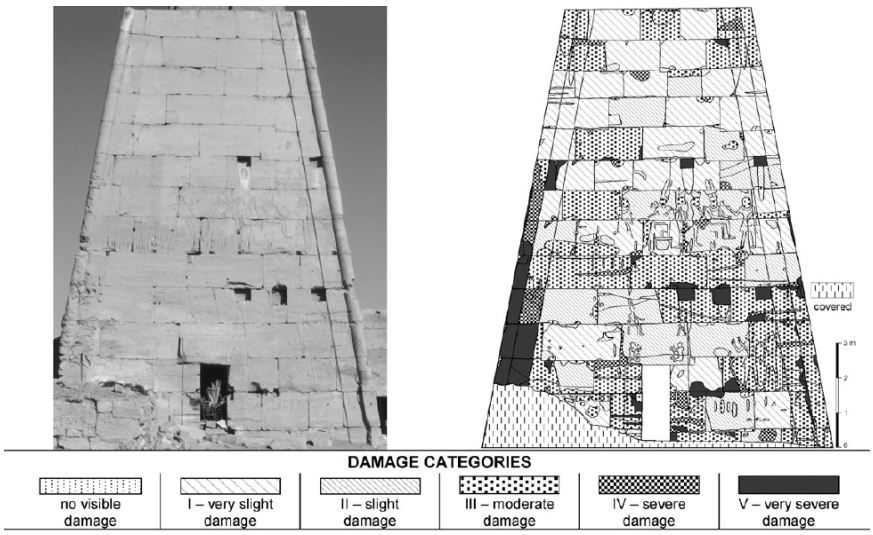


Figure 4. Part of monument with blocky heterogeneous structure due to spatial variability of damage and stone properties.

The way things will be done seems optimal, that is to say:
1) gather your field data and do your geostatistics with KRIGSTAT package developed by TUC
2) generate a FLAC3D or 3DEC or any other grid used by the partners who perform numerical modelling and export your zone centroids or Gauss integration points
3) generate material properties at the zone centroids using geostatistical code KRIGSTAT
4) import the above properties into FLAC3D or 3DEC or other and run your analysis.

b - Identification of the Constitutive Laws (material behavior) for the different materials and elements (TUC, UPV/EHU).

Usually, only few characteristics among many dominate the response of a complex mechanical system. The goal of theory is to identify them and condense them into rationally derived but simple laws describing, at least approximately, the overall behavior of the system. These laws are the constitutive laws that should consider apart from mechanical and damage response also the various diffusion processes inside the porous materials (moisture transport, heat conduction, etc.) that affect the behavior of the structure (e.g. Fig. 5). The new field of 'chemomechanics' will be further elaborated in the frame of this project for **porous damageable geomaterials in monuments**. The aim of this subtask is the formulation and implementation of simple chemomechanical constitutive laws in the numerical tools for the predictions of the mechanical behavior of

the virtual monuments.

Fig. 5. (a) Damage of interior brick wall due to salt diffusion (transport) and crystallization, and (b) crack propagation in exterior brick wall (Waag building in Amsterdam).

As a result from the reliability analysis is obtained:

- the failure probability
- the sensitivity parameters.

The failure probability has to be compared with some preset target values. The sensitivity coefficients direct towards the main parameters that have to be dealt with in the preservation process (or: DST).

Validation of the Probabilistic Risk Assessment Model will be performed for the selected case studies to demonstrate its added value. Starting from simple analytical examples toward more complex applications, involving FEM//DEM analysis. It will contain:

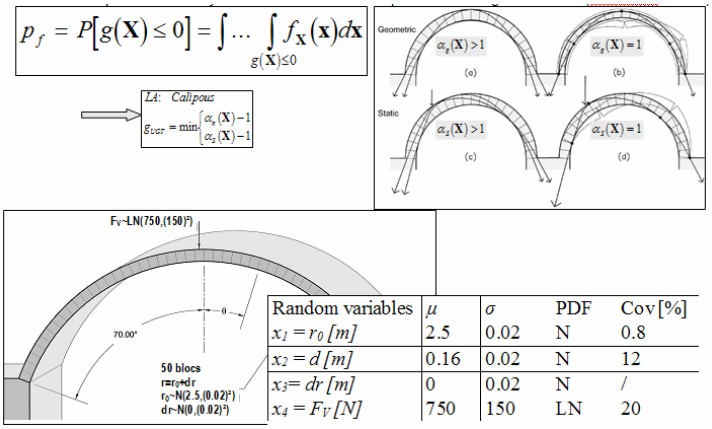
- Studies on the vulnerability of ancient structures in seismic prone areas
- Safety assessment of masonry arches – church of Sint-Jackobs, Leuven (B) (KULeuven): effect of accurate geometry on the safety assessment, Fig. 6. This incorporates the following steps:

  Step 1. Accurate geometry (**Task 8.1**) 3D-scanning – establishing point-cloud and images, See WP2 (KULeuven/ASRO, CNR-ICVBC/ISTI) of selected monuments;

  Step 2. Construction of the discrete model for the limit analysis in CALIPOUS;

  Step 3. Definition of the parameters involved. A probabilistic model is put forward for the model parameters involved. A Non-Tension Material will be used, with bounded compressive strength;

  Step 4. A limit analysis of arches and vaults is performed using CALIPOUS (KULeuven/ASRO)[4].



Random variables	μ	σ	PDF	Cov [%]
$x_1 = r_0$ [m]	2.5	0.02	N	0.8
$x_2 = d$ [m]	0.16	0.02	N	12
$x_3 = dr$ [m]	0	0.02	N	/
$x_4 = F_V$ [N]	750	150	LN	20

Figure 6: Safety assessment of masonry arches.

UPV/EHU will collaborate with the partnership to include the chemical and biological stressors among the factors affecting the probabilistic risk assessment because this model cannot be defined without the approach of the influence of chemical reactions on materials and the existence of degradation products. Biological Parameters obtained from WP6 will be taken in account during validation of the probabilistic risk assessment model. The UPV/EHU participation will come also from our expertise on the chemical point of view of the effects of the environmental and biological impacts and the corresponding consequences if the proposed corrective actions are not taken into account.
Partners involved: UPV/EHU, KUL, TUC, SMARTEC,INNOWEP,UPC,IPPT,

Milestones & Deliverables

ML8.1 – Calibrated simulation models for analytical and numerical analyses uploaded in Mach's Platform
ML8.2 - Upscaling software and parameter identification software of constitutive laws of geomaterials by virtue of Damage Mechanics, Scaling laws and fuzzy logic,
ML8.3 - Chemomechanical constitutive laws for damageable porous natural and artificial geomaterials embedded in 3DEC.
D8.1: - Discrete Interactive 4D virtual monument model
D8.2: Analytical and numerical simulation tools
D8.3 - Probabilistic Risk Assessment tool

Workpackage number	**9**	**Start date or starting event:**				**T19**	
Workpackage title	**Decision Supporting Tool**						
Activity type[1]	**RTD**						
Participant n°	ICVBC	UPV/EHU	KUL	TUC	SINT	SMARTEC	INNOWEP	UPC
Person-months per participant	0.5	2	5	4	0.5	1	0.5	6
Participant n°	UROMA1	ITAM	IPPT	BAM	TNO	UMINHO	TT	Total
Person-months per participant	4	4	1	2	5	2	1	**38.5**

Objectives

The final DST is an expert system, in the form of a software, able to (1) acquire rellevant information on a specific monument under study from the MaP and (2) capable of support decisions related to different phases of the study (assessment of the state of conservation, inspection, monitoring, risk assessment) and particularly (and above all) supporting the decisions related to scheduled maintenance and intervention.
This will be developed integrating all the information gathered in the process of the comprehension of a monument as a whole and will be based on the characterization of the state of decay and damage, the residual life, the structural safety and the existing risks. Based on the comprehension of the physical processes involved, the DST will provide a prognosis on the evolution of damage, residual life, safety and residual risks in the medium and long term. In turn, this information will permit the identification of repair, strengthening and maintenance needs. The ultimate purpose of the DTS is to provide a programme for

preventive maintenance (scheduled maintenance) to be developed according to optimal time (schedule) and cost requirements.

Description of work

The work package involves the following activities:

1- **Procedure for damage characterization.** Based on the evidence and criteria yield by the previous WP's and particularly by those related to interpretation, inspection, monitoring and structural analysis, a general procedure will be formulated for the integration of information and identification of the condition of historical structures. The evidence gathered through the previous WP's will be utilized to identify causes or phenomena contributing to material decay and structural damage and to characterize the role of the different possible actions (climatic environmental, chemical, biological, mechanical, geotechnical, anthropogenic…). For that purpose, existing MDDS (Monument Damage Diagnostic System) resulting from previous research projects on conservation will be considered and adapted to the MACH philosophy of preventive conservation and scheduled maintenance..

   Particular attention will be paid to the contribution of non-destructive and minor-destructive techniques to classify and quantify the damages. Among other sources, the Compendium on NDT methods developed by BAM will be considered as a starting point. Parts of this database concerning methods to be applied at cultural heritage buildings and structures will be integrated into the MaP. Direct links from the damages contained in it to NDT and MDT methods will help the end-users to select the appropriate methods and to develop fast and efficient strategies for building assessment.

   The procedure will be calibrated and validated through its application to the different case studies.

   All partners are involved in the activities related to the integration of information obtained from previous WP'. In addition, specific contributions are expected from INNOWEP, ITAM, IPPT and UMINHO (procedure for damage characterization, damage assessment by ambient vibration), TNO (adapting existing MDDS), and BAM (link to data base NDT methods).

2- **Risk assessment.** The evaluation of the performance of the construction involves the analysis of the *structural safety* and the assessment of the *risks* to both people and cultural contents. Structural safety and risks will be analyzed for the present condition and, as a prognosis, for the future condition of the building at short, medium or large terms. Safety and risk evaluation will be carried out taking into consideration structural and non-structural phenomena.

   Structural safety can be estimated using reliability-based methods leading to the characterization of the global probability of failure (see in Schueremans and Van Gemert, 2004). The analysis of residual life and risk can be carried out based, in particular, on the generalized load (S) and resistance (R) models (see Melchers, 1999). Damage, in the form of damage rate vs. time curves, will be predicted at each critical part of the monument subjected to various types of future actions (mechanical and environmental). For this purpose, the numerical models formulated in WP8 (as, in particular, those accounting for the simulation of degradation processes) are of large importance.

   The difficulties and limitations affecting the actual possibility of determining or estimating structural safety and risks in structures of architectural heritage are to be carefully analyzed together with their impact on the reliability of the tools produced.

   The impact of maintenance in the degradation process will be embedded in the analysis in order to offer a tool for the design optimal preventive maintenance strategies. These predictions will be used as a reference for the establishment of the best maintenance strategy (best in terms of cost and

effectiveness).

UPV/EHU, UPC, TUC and UMINHO will cooperate in the risk assessment using, in particular from numerical results obtained from WP8 and the simulation of damage scenarios. KUL will lead the activities oriented to evaluation of structural safety and risk analysis while TNO will take care of risk analysis for non-structural damage.

3- **Identification of maintenance needs and strategies.** Possible strategies will be formulated and then simulated using the tool developed for the analysis of residual life. The maintenance strategies to be analyzed will consider a set of widespread possibilities, including the setting of "barriers" in order to stop the impact of the environmental actions or the selection of adequate cleaning, protecting or consolidating procedures.

In particular, the maintenance strategies and techniques considered will be evaluated on account of their compliance with conservation principles and good practices. Conservation principles (such as minimal impact, compatibility, reversibility, non-invasivity) will be considered to select optimal or adequate actions. In particular, the impact of the different techniques and strategies on the cultural value of the buildings will be evaluated as a way to determine their acceptability and opportunity.

Optimal repair or maintenance strategies will be proposed and selected by analyzing the way they satisfy the following criteria: (1) Impact on the residual life (capacity to enlarge the life of the construction) and (2) degree of alignment with conservation principles and resulting cultural costs caused by the implementation of the maintenance strategy. A cost-benefit analysis may be carried out to decide among different possibilities.

All the partners are involved in the identification of maintenance needs, identification of parameters to be monitored as preventive measures, identification and selection of strategies, and cost benefit analysis, KUL, UNROMA1, IPPT and TNO will cooperate in the proposal and evaluation of exemplary maintenance strategies on case studies in close collaboration with typical end-users (Monumentenwacht Vlaanderen, Monumentenwacht Nederlan and other).

4- **Methodology for estimation of costs and time requirements.** Based on the information and criteria rendered by the previous activities, a procedure will be formulated to estimate the costs and terms involved in the development of the maintenance programmes. Cost and time will provide another criterion (together with the above mentioned (1) and (2)) which, once implemented in the DST, will help deciding about the best maintenance strategies and the way they should be developed in practice. The estimation of costs and time will stem from a summary of data on maintenance and repair costs based on specific case studies including also life cycle of materials and conservation /restoration interventions.

Partners involved in this activity are UPC and ICVBC (general procedure), ITAM (summary of data and maintenance or repair costs), UNROMA1, TT, TNO, KUL (application to case studies in collaboration with typical end-users).

5- **Decision Supporting Tool (DST).** This activity involves the construction of the DST based on the outcome of the previous items. The DST will consist of an expert system able support the user (assist decision taking) on the different operations involved in the study of a building (documentation, diagnosis, analysis) and particularly to support decisions related to intervention and scheduled maintenance. The DST will stem as a synthesis of all the results and experience yield by the project. The issues related to Damage, Assessment, Intelligent Monitoring, Simulation and Risk Analysis (DAMSRA) will be implemented based on an integrated understanding –the DAMSRA concept. The DST will thus promote and sustain conservation programmes based on the comprehension of decay /

damage processes of a Monument as a Whole.

The essential Module of the decision support tool will consist of a digital guideline involving the following sections: (1) assessment and documentation of the state (of conservation) of the monument as a whole; (2) analysis and diagnosis of decay phenomena; (3) risk analysis (including environmental influences); (4) Intervention; (5) Maintenance planning, including monitoring. The MDDS prototype created within the EU project COMPASS will be considered as a starting point and will be extended to produce a complete tool complying with the DAMSRA concept.

Once made available, the DST will be applied to the selected case studies as a way to validate its actual applicability in the definition of a protocol oriented to their future maintenance and continuous monitoring. The validation of the DST will be carried out with the contribution of the different end-users involved in the project by evaluating its performance when applied to different case studies.

Particular attention will be paid to adequately connect the DST to 3D representation and documentation to assure effective monitoring accessible to owners and maintenance oriented organizations and SME's. The DST will lay on a European platform (MACH platform) and will be made accessible in the future to the stakeholders of the European Monumental Heritage.

All the partners are involved in this final activity and particularly to its application to case studies and validation. TNO, SINT, TUC, and UPC will cooperate to the development of DST and its integration to the MACH platform and KUL and ICVBC will contribute, in particular, to its connection to 3D representation and documentation.
TT will cooperate with BAM for the exploitation of the DST

References

- BAM. Compendium on NDT methods (in German, soon be available in English). http://www.bam.de/microsites/zfp_kompendium/welcome.html
- Compatibility of Plasters and Renders with Salt loaded Substrates in Historic Buildings (COMPASS). EU Project, contract No: EVK4-CT-20010047-DG XII. http://www.compass-salt.org/
- Melchers R.E., "Structural Reliability, Analysis and Prediction", Ellis Horwood Series in Civil Engineering, 1999.
- Schueremans L., Van Gemert D., "Assessing the safety of existing structures: reliability based assessment framework, examples and application", JCEM Journal of Civil Engineering and Management, Lithuania, Issue 2, Vol X, June 2004, pp. 131- L.
- Schueremans, L., Van Gemert, D. "Assessing the safety of historical masonry structures", Modern Building Materials, Structures and Techniques, Vilnius Gediminas Technical University, May 19-21, 2004. 141.

Milestone & Deliverables

ML9 – Expert software for damage state - residual life- maintenance strategy - Cost & Time analysis and its integration in the Mach platform

D9 - Decision supporting Tools (DST) for monuments conservation

Table 1.3d Summary of staff effort

WP	Tasks	ICVBC	UPV_EHU	KUL	TUC	SINT	SMARTEC	INNOWEP	UPC	UNROMA1	ITAM	IPPT	BAM	TNO	UMINHO	TT	tot Task	Tot WP
1																		
	1,1	3															**3**	**20**
	1,2	2	1	1	1	1	1	1	1	1	1	1	1	1	1	1	**16**	
	1,3	1															**1**	
2																		**43**
	2,1		1	2			0,5		1	4	1	1		1	1	1	**13,5**	
	2,2	7		9							1,5	6			6		**29,5**	
3																		**12,5**
	3,1		1	1			0,5		0,5	0,5	2	0,5	0,5		0,5	1	**8**	
	3,2	0,5	0,5		0,5	0,5		0,5			1		0,5	0,5			**4,5**	
4																		**17,5**
	4,1	1	2	0,5	0,5	0,5	1	0,5		0,5	1	0,5	0,5	1	0,5	1	**11**	
	4,2	4			2,5												**6,5**	
5																		**66,5**
	5,1	2,5	0		2	5,5	6				1	1					**18**	
	5,2	0,5	7	2	2	20		9			1	**2**	3		2		**48,5**	
6																		**65**
	6,1	0,5	1	0,5	0,5	0,5	0,5	0,5	1	1	0,5	1	1	1	0,5	1	**11**	
	6,2		1	3,5		4,5	2,5			1	3	2	1		2,5		**21**	
	6,3	3	5		0,5	5		5,5				2	3	4			**28**	
	6,4	0,5	2						1		0,5	1					**5**	
7																		**13**
	7,1		1,5	0,5		1	1	0,5	0,5	0,5			0,5			1	**7**	
	7,2	0,5	2								0,5	0,5	0,5	0,5	0,5	1	**6**	
8																		**52,5**
	8,1	3	3	3	9,5				2	4		0,5	2	1	5		**33**	
	8,2		3	4	6		2	2	2			0,5					**19,5**	
9		0,5	2	5	4	0,5	1	0,5	6	4	4	1	2	5	2	1	**38,5**	**38,5**
10		0,5	3	1	0,5	1	1	1	0,5	0,5	1	1,5	3	1	0,5	3	**19**	**19**
Tot		**30**	**36**	**33**	**29,5**	**40**	**17**	**21**	**15,5**	**17**	**19**	**22**	**18,5**	**16**	**22**	**11**	**347,5**	**347,5**

Table 1.3e List of milestones

Milestone number	Milestone name	Work pakage(s) involved	Expected date	Means of verification
ML1	Critical path definition	**WP1**	**M1**	Consortium agreement
ML2	Survey of selected cases studies: geometrical – topographical data collection	**WP2**	**M3**	Field survey completed and data quality validated.
ML3	The State of the Art of diagnosis and monitoring of monumental CH	**WP3**	**M3**	Literature survey completed
ML4	Data homogenisation and definition of their format	**WP4**	**M4**	Software released and validated by a user group
ML5.1	Design and development of a wireless sensor network Improvement of the FOS system	**WP5**	**M11**	Field prototypes completed and running flawlessly
ML5.2	Validation of the developed wireless systems, with respect to conventional systems	**WP5**	**M43**	WSN field validation tests
ML5.3	Design and development of new portable diagnostic devices	**WP5**	**M12**	Portable prototype completed and running flawlessly
ML6.1	Establishment of Diagnosis and Monitoring protocols	**WP6**	**M12**	Draft for on site operative procedures
ML6.2	Installation of the FOS and wireless monitoring system (WSN) at the benchmark test sites	**WP6**	**M12** **M14**	In situ prototype completed and running flawlessly
ML6.3	Data elaboration and integration	**WP6**	**M41**	Field survey complete and data quality validated.
ML7	On site validation of new and improved methods and technologies for on site diagnosis	**WP7**	**M41**	On site methods and technologies validated by user group.
ML8.1 **ML8.2**	Calibrated simulation models for analytical and numerical analyses uploaded in Mach's Platform - Upscaling software and parameter	**WP8**	**M40** **M47**	-Verification & Validation of the models with clearly established procedures. - Software released and validated by the

ML8.3	identification software of constitutive laws of geomaterials by virtue of Damage Mechanics, Scaling laws and fuzzy logic - Chemomechanical constitutive laws for damageable porous natural and artificial geomaterials embedded in 3DEC.		**M47**	user group
ML9	DST for damage state - residual life-maintenance strategy - Cost & Time analysis and its integration in the Mach platform	**WP9**	**M47**	Software released and validated by the user group

1 Measured in months from the project start date (month 1).

2 Show how you will confirm that the milestone has been attained. Refer to indicators if appropriate. For example: a laboratory prototype completed and running flawlessly; software released and validated by a user group; field survey complete and data quality validated.

2. Implementation

2.1 Management structure and procedures

Describe the organisational structure and decisionmaking mechanisms of the project.
Show how they are matched to the complexity and scale of the project.
(Maximum length for 2.1: 5 pages)

The coordinator ICVBC will manage the partnership (WP1) with the aim to create a collaborative team with a strong awareness of the common work to be fronted in order to achieve the objectives proposed and will continuously keep up the progress of results and scheduled dead lines for milestones, contributing to maintain on time the production of the deliverables.

The critical path (**ML1**) determines the total calendar time required for the project The 4 year duration are determined by adding the time for the development of innovative monitoring system and portable diagnostic tools (about 1 year) to the longest path: the monitoring activities for at least 3 time steps and 4 time steps for checking the seasonality of some parameters (about 3 years). For each Milestone the following quantities have been considered:

ES = Earliest Start Time – EF = Earliest Finish Time – LS= Latest Start Time – LF = Latest Finish Time

The LS and LF are the critical points that an activity can start and finish without delaying the project. As the project unfolds, the estimated times are replaced by actual times and in case where there are some delays the resources may be shifted to stay on schedule. The best solution is that none of the activities have slack (difference in the LF and EF).

The coordinator is the interface between the consortium and the EC and continues contacts with the Scientific Officer in charge of the project will be kept. Regular exchange of data and information will be usually made by e-mails and through the up-down load of documents and data (worksheets) in the restricted area of the MACH web site maintained by ICVBC. In this site will be posted all the

documents produced in the project and a Thing to Do (**TtDo**) list will be evidenced and continuously update.

At the kick-off meeting (KOM = T_{0+1}) the initial guideline to identify the monuments from a stylistic and constructive point of view will be elaborate [WP2 – **D2.1**] together with the establishment of the data format for the web driven Mach Platform [WP4 – **D4**] and the preliminary draft of the Exploitation plan (WP10 – **D10.E1**].

Scheduled Project Workshops (**PW**) as management meetings for: the jointly discussion of the results achieved, elaborate the material for the reports, approval and organization of further steps, will be organised at: **PW1** T_{0+9} – **PW2** T_{0+17} – **PW3** T_{0+33} – **PW4** T_{0+41}. Particular engagement will be put for the Mid-Term Assessment Meeting (**MTM** T_{0+24}) and the Final meeting (**FM** T_{0+48}).

Interim and periodical reports on the ongoing works will be redacted, at the expected time (**D.R** = T_{0+1} - T_{0+6} - T_{0+12} - T_{0+24} - T_{0+36} - T_{048}), together with the financial cost statements (**D.C** = T_{0+12} - T_{0+24} - T_{0+36} - T_{048}) and required audit certification (**AC** = T_{0+24} - T_{0+48} the first after 2 years and the second after 4 years at the completion of the project).

The project is divided into 10 Work packages, each one handed by a leader, characterising the different aspects of the whole structure:

WP Leaders:

WP2 – KUL; **WP3** – ITAM; **WP4** – ICVBC; **WP5** – SINT; **WP6** – IPPT; **WP7** – UPV/EHU; **WP8** – TUC; **WP9** – UPC; **WP10** – BAM.

Each leader will organise the specific contributes of the partners involved in his/her WP, assessing and stimulating the progress of results (achievement of the milestones and realization of deliverables) with a continue exchange of information with the coordinator.

Each WP leader have to respect the time limit established for the milestones belonging to the WP itself and would monitor for possible delay and obviate with adapt interventions. The temporal sequence of the work is reported in the Gantt diagram (pag 12) while the structure of the project is reported in the Perth diagram (pag 13).

The realization of some WPs or Tasks requires the jointly effort of all partnership such as:

- WP1 for management activities, cost statements and project's meetings;
- WP3 Task 3.1, for the elaboration of the state of the art in the field of monitoring and diagnostic for Cultural Heritage and for the exploitation of past EC funded projects;
- WP4 Task 4.1, for the definition of data format and the structure of the Mach Platform;
- WP7 for the elaboration of recommendation and guidelines of reliable techniques and methods,
- WP9 for the final elaboration of the data collected in the project and the realization of the final expert system (DST) for the diagnosis and the scheduled maintenance of a "Monument as a Whole";
- WP10 for the collective dissemination and exploitation of the results achieved.

Other WPs needs specific competences such as: WP2, WP5, WP6 and WP8.

At the initial phase of the project in the WP2 architects, historians and scientific staff will characterise the selected monumental sites (see part 1.3), with the realization of a specific data base (**D2.2**):

ML2 - Survey of selected cases studies: geometrical – topographical data collection
ES = T_{0+1} – EF = T_{0+2} – LS = T_{0+02} - LF = T_{0+3}.

Starting from ML2 experts in image elaboration (from KUL, UMINHO, IPTT and ICVBC-ISTI) will construct the 3D models of the monumental test site selected producing their graphical representation.

The first version of the 3D models will be ready at T_{0+15} [**D2.3**]. This is a quantitative-visualization tool containing all the structural and non-structural key elements affecting the performance of the monument. It will further improved (T_{0+18}) and calibrated with in situ monitoring measurements (T_{0+17} - T_{0+29} and T_{0+41}) and integrated into the MACH platform (T_{0+30}) where the required finite or distinct element model is constructed and used in WP8 for the finite element analysis of the selected monuments (T_{0+43} - T_{0+44}).

In parallel will start the WP3 in which will be jointly examined and discussed the state of the art in the monitoring and diagnosis of monuments, enclosed the outcomes of EC funded projects in the field.

ML3 - The State of the Art of diagnosis and monitoring of monumental CH
ES = T_{0+1} – EF = T_{0+2} – LS = T_{0+02} - LF = T_{0+3}.

On the basis of such an examination a data base will be built [**D3** - T_{0+3}] also containing information taken from successful outcomes of past EC funded projects.

At the same time the WP4 will begin and after having jointly discuss and established the opportune data format:

ML4 - Data homogenisation and definition of their format
ES = T_{0+1} – EF = T_{0+3} – LS = T_{0+02} - LF = T_{0+4}.

The web driven MACH Platform (MaP) will be design and built mainly by TUC in collaboration with CNR-ISTI. The beta version will be ready at T_{0+15} [**D4**] and updated at T_{0+18} and T_{0+30}. It will contain an interactive (mining) Data Base (ML) in which will be stored all data (raw and filtered), coming from literature and collected by stationary sensors (WSN and FOS) and determined by portable diagnostic tools in monitoring campaigns (T_{0+43}). In the MaP the historical and architectural data (WP2) togheter with simulation tools developed in WP8 (T_{0+43}) and the final DST (T_{0+48}) will be integrated.

The ICVBC and his sub contractor UniSiena in collaboration with SINT/HTS will design and develop the innovative Wireless Sensor Network (WSN) using commercial and custom dedicated sensors' modules interconnected with a commercial standard Kmote wireless system (T_{0+12}). The SMARTEC will develop and improve the FOS system.

ML5.1 - Design and development of a wireless sensor network. Improvement of the FOS system
ES = T_{0+1} – EF = T_{0+14} – LS = T_{0+02} - LF = T_{0+15}.

The first prototype of the open WSN and the 3 FOS systems will be assembled [**D5.1 -** T_{0+12}]. The WNS will be tested and verified in a monumental site in Florence (T_{0+14}). After then, two tailored WSN will be prepared and installed: one at the Borbonic jail and in some buildings of the Graziella quarter Ortigia (Siracusa); the second at the tower of the cathedral of Porto (Porto). In the first case the WNS will be correlated with some critical points of the Borbonic jail monitored by FOS, while the second one will be correlated with some critical points of the tower monitored by standard cabled sensors. The other two FOS systems will be tailored and mounted at Saint Jacob (Levuen) and Saint John (Gandsk) for their comparison with standard cabled sensors. In parallel the vibrating monitor device will be operative [**D5.1.1**] and applied at Ortigia.

The SMEs involved (SINT and INNOWEP) will start immediately (T_{0+1}) to design and develop the innovative portable diagnostic tools (WP5).

ML5.2 - Design and development of new portable diagnostic devices
ES = T_{0+1} – EF = T_{0+12} – LS = T_{0+02} - LF = T_{0+13}.

The realization of operating prototypes [**D5.2.1** - Hole drilling; **D5.2.2** Drilling Resistance; **D5.2.3** – CoDiT; **D5.2.4** - Surface meter; **D5.2.5** – Active Tomography; **D5.2.6** – NDT Chemical test; **D5.2.7** -

NDT Biological test] will be ready at (T_{0+12}) and after lab and on site functional tests validated at (T_{0+14}).

The campaigns (WP6) for monitoring the selected parameters will start after the achievement of :

ML6.1 - Establishment of Diagnosis and Monitoring protocols
ES = T_{0+10} – EF = T_{0+12} – LS = T_{0+11} - LF = T_{0+13}.

ML6.2 - Installation of the FOS and wireless monitoring system (WSN) at the benchmark test sites
For FOS - ES = T_{0+13} – EF = T_{0+14} – LS = T_{0+14} - LF = T_{0+15}.

For WSN - ES = T_{0+16} – EF = T_{0+17} – LS = T_{0+17} - LF = T_{0+18}.

The FOS systems once tailored for its application in the 3 sites will be installed and managed by SMARTEC) at T_{0+13} in order to follow the behaviour of selected structural parameters for a longer period of time. The WNS needs to be designed, developed and verified and can not be fully operative on sites before T_{0+17}.

ML6.3 - Data elaboration and integration
ES = T_{0+14} – EF = T_{0+41} – LS = T_{0+15} - LF = T_{0+42}

The WSN and FOS will collect, record and transmit data from sensors in continuous while other data will be determined with periodical on site measurements at T_{0+17} - T_{0+29} and T_{0+41} using portable devices and technologies. The evaluation of the influence of seasonality will start at T_{0+17} and will be followed at $T_{0+26,}$ T_{0+34} and T_{0+41}. All the data (raw or filtered) will be recorder in the interactive Data Base [**D6.2**] integrated in the Mach Platform, while the stationary sensor's location (and ongoing value) will be geo-referenced and visualized on the discrete interactive 4D models [**D8.1**], The evaluation of seasonality on some environmental parameters will used for draft seasonality charts [**D6.3**]

ML7- On site validation of new and improved methods and technologies for on site diagnosis
ES = T_{0+29} – EF = T_{0+41} – LS = T_{0+30} - LF = T_{0+42}

The different techniques and methodologies after a ranking of their capacities to exactly quantify the parameters needed for establish the risk assessment of a monument as a whole and schedule its preventive maintenance will be suggested for their standardisation (WP7) and recommendations and guidelines will be drafted [**D7 -** T_{0+44}].

ML8.1- Calibrated analytical and numerical DEM and FEM model as simulating tools
ML8.2 - Upscaling software and parameter identification software of constitutive laws of geomaterials by virtue of Damage Mechanics, Scaling laws and fuzzy logic
ML8.3 - Chemomechanical constitutive laws for damageable porous natural and artificial geomaterials embedded in 3DEC

ES = T_{0+12} – EF = T_{0+47} – LS = T_{0+13} - LF = T_{0+48}

Aanalytical and numerical models will be developed (WP8) in order to evaluate the damage state and to assess the residual life, together with a model-free statistical analysis of continuous monitoring data to extract novelty functions as possible indicator of changes in the weathering behaviour.
Last generation of analytical and numerical Simulating Tools [**D8.2 -** T_{0+45}] together with the Probabilistic Risk Assessment Model [**D8.3** T_{0+45}] will be used for assisting the selection of the best design of the intervention (maintenance) method.

All numerical models will be uploaded in the Mach's Platform and will be used for the prediction of short, medium and long-term behavior of the monumental buildings under observation at all scales for the application of the best maintenance or protection strategy

ML9 - DST for damage state - residual life- maintenance strategy - Cost & Time analysis and its integration in the Mach platform
ES = T_{0+19} – EF = T_{0+47} – LS = T_{0+20} - LF = T_{0+48}.

The final expert Decision Supporting Tool (*Probabilistic Risk Assessment Model and Life Prediction of a Monument as a Whole)* will be established [**D9 -** T_{0+48}]

The exploitation plan [**D10.E**] will start at T_{0+1} and will be continuously improved, updated and approved during the scheduled Project Workshops, in all its specificities : activation of the MACH Web site at T_{0+4} [**D10.W**], organisation of two seminaries during a project workshop [**D10.SW**] at T_{0+25} and T_{0+41}; organisation of a training course at T_{0+46} [**D10.T**] and the publication of the results of the project in scientific papers and their presentation in specialised International Conferences [**D10.P**].

2.2 Individual participants
For each participant in the proposed project, provide a brief description of the organisation, the main tasks they have been attributed, and the previous experience relevant to those tasks. Provide also a short profile of the staff members who will be undertaking the work.
(Maximum length for 2.2: one page per participant)

P1 – CNR ICVBC
Consiglio Nazionale delle Ricerche. Istituto per la Conservazione e la Valorizzazione dei Beni Culturali, Sesto Fiorentino - Italy

The Institute for the Conservation and Valorisation of Cultural Heritage, was recently established in Florence (2002) merging three former research centres on the "Cause di Deperimento e Metodi di Conservazione delle Opere d'Arte" of Florence, Milan and Rome, the last two constitute the territorially independent units. The scientific activity of the Institute and the competences of the personnel together with the instrumentation available let to develop advanced researches in the field of scientific methodologies applied for the conservation and promotion of the Cultural Heritage. The institutional objectives and strategic targets are:

- Characterization and qualification of cultural assets.
- Set up of new technologies and materials for the conservation of cultural heritage.
- Development of new criteria for planning and implementing restoration/conservation procedures.
- The study of the state of conservation of historical buildings and archaeological remains.
- Development of protective and consolidating products for monumental stones
- Monitoring of monuments with the identification of the most suitable parameters for the elaboration of models and evaluate the decay rate of sheltered and unsheltered monuments.

Main tasks in the project

The ICVBC is the coordinator of the project and will be involved in its management (WP1). ICVBC is the representative of other CNR Institutes (ISTI and IA) which are collaborating in the proposal. For what concern the research activities the ICVBC is WP leader of WP4 in which all data produced in the project will be integrated in the web driven Mach platform and will contribute to the Task 6.1 - Deterioration phenomena and processes: Selection of parameters, methods and protocols definitions, Task 6.3 - No-structural diagnostic and Materials decay. Furthermore, it will participate at the common work scheduled for the other WPs of transversal

(horizontal) character, that is to say, in WP3, 4, 5, 7, 9 and in particular to WP10 - Dissemination and exploitation.
In collaboration with colleagues from CNR-ISTI will contribute to the Taks 2.2 Construction and processing of the 3D models of selected monuments required to support input data for structural analysis, and to the design of the interactive system supporting real-time, web-based mapping of sensor data for their visual presentation which should be geo-referenced to the 3D representations. Furthermore, ISTI will investigate in Task 8.1 new solutions for the semi-automatic construction of meshes for structural analysis from dense scanned pointset. Structural analysis (static and dynamic analysis, modelling of strengthening operations, limit analysis) of the selected monuments via the finite element code NOSA developed by ISTI-CNR. With the activity developed in a research sub contract, to be attributed to the University of Siena, Dept. of Information Engineering, will contribute to the Task 5.1 Design and implementation of a Wireless Sensor Networks Prototype (WSN). In collaboration with CNR-IA will participate at the WP6.3 for the application on site of the ACEADD methodology.

Research staff involved:

CNR - ICVBC
Piero Tiano – *Coordinator*
Fabio Fratini – Researcher, geologist expert in petrology and in mortar and lime based concrete materials.

Piero Tiano is a Senior Scientist, with more than thirty years of experience on the study of scientific problematic related to the conservation of the cultural heritage. In depth knowledge of decay processes on monumental stones and in conservative actions to preserve them. Head of the technological section focused to the development of new methodologies for the determination of relevant parameters for stone characterization and for the quality assurance of the restoration procedures. He is member of National Commission for the Normative on Stone Artifacts UNI-NORMAL, of the European CEN TC 346 Conservation of Cultural Property - Working Group 3, and of the WG1 in the Focus Area CH (Cultural Heritage) of the European Construction Technological Platform (ECTP). He has been an expert evaluator for the EC in the SMT EC call for proposal (February 1998), and in the City of Tomorrow EESD- 3 call (March 2001). Internet evaluator for INTAS (id number: 1228) from May 1999.
He has been the coordinator of fourhree EC funded projects relevant for the proposal:
- HARDROCK (Contract: SMT4-CT96-2065) Development of a new method to determine the superficial hardness of exposed monumental rocks.
- BIOREINFORCE (Contract EVK4-CT2000- 00037) Biomediated Calcite Precipitation for Monumental Stones Reinforcement.
- McDUR (Contract G6RD-CT2000-00266). Effects of the Weathering on Stone Materials: Assessment of their Mechanical Durability
- MOMOREX (Agreement CLT2003/A1/CH/IT-172). European façades painted during the XVI century: model of a project for the monitoring of deterioration subsequent to recent restoration.
Furthermore, he has been a partner in the following EC projects:
- DIAS (Contract EVK4-CT2002-00080) Integrated tool for in situ characterisation of effectiveness and durability of conservation techniques in historical structures.
- OSNET (G1RD-CT2001- 05019) Thematic network on ornamental stones

Recent publications

Tiano Piero, Fratini Fabio, Rescic Silvia, Cantisani Emma, Mencaglia Andrea, "Stress superficiali indotti dalla lavorazione dei materiali lapidei: Il caso della pietra saponaria utilizzata nel restauro della cattedrale di Nidaros (Trondheim-N). ARKOS, n 11, Anno VI, Luglio-Settembre 2005, Nardini Editore, pp 47-53.

Tiano. P., *Innovative treatments for stone conservation.* Corrosion Review, vol 22 n 5-6, 2004, pp 365-380.

Tiano, P. E. Cantisani, S. Fantechi. *Genesis and Microstructure of the Marble: their influence on the durability of the material used in historical buildings and sculptures.* 32° IGC, Firenze , 20 - 28 August 2004

Tiano P., S. Rescic and E. Valentini. *New diagnostic tool for "in situ" evaluation of conservative treatments for monumental stones.*Eastern Analytical Symposium, 2004 November 15 - 18, Somerset, NJ, USA.
Fratini F., Rescic S., Tiano P., *A new portable system for determining the state of conservation of monumental stones*. Materials and Structures 39, n 2 , March 2006, 125-132
Tiano, P., Cantisani E., Sutherland, I., Paget J.M. B*iomediated Reinforcement of Weathered* Calcareous Stones. Journal of Cultural Heritage 7, 2006. 49-55.
Kubičár, L', V. Vretenár, V. Boháč and P. Tiano "*Thermophysical Analysis of Sandstone by Pulse Transient Method*" Int. J. of Thermophysics, Volume 27, Number 1 / January, 2006, 220-234

CNR - ISTI

The Istituto di Scienza e Tecnologie dell'Informazione (ISTI), an institute of the Italian National Research Council (CNR), is committed to producing scientific excellence and to playing an active role in technology transfer. The domain of competence covers Information Science, related technologies and a wide range of applications. The activity of ISTI-CNR aims at increasing knowledge, developing and testing new ideas and widening the application areas.

Visual Computing Laboratory
The Visual Computing Lab, one of the research departments of ISTI, has been active on visualisation and computer graphics since 1984. Research in graphics algorithms currently focuses on the design of algorithms, data structures and prototypal systems for scientific visualisation (with particular emphasis on volume datasets), 3D surface-based graphics (efficient multiresolution representation and rendering of huge datasets), automatic acquisition of digital 3D models, and soft tissue modelling. The current main fields of application are cultural heritage and medicine.
The Visual Computing Lab is actively involved in EU funded projects, such as the IST NoE "EPOCH", IST NoE "Aim@Shape", IST FET "CROSSMOD" or the recently terminated IST Strep"ViHAP3D".

Mechanics of Materials and Structures Laboratory
The Mechanics of Materials and Structures Laboratory is a joint research group constituted by some researchers from ISTI-CNR and the Dipartimento di Costruzioni of University of Florence (http://www.isti.cnr.it/ResearchUnits/Labs/mms-lab/). Since 1979 the Laboratory carries out research and software development in the field of solid mechanics, with particular focus on structural engineering. The main research subjects are:
- Mathematical modelling in continuum thermomechanics: constitutive equations of materials, with particular emphasis on non-linear elastic, elastic-plastic and masonry materials; study of equilibrium and evolution problems in solid mechanics.
- Numerical methods for the solution of equilibrium and evolution problems.
The models studied and the algorithms formulated have been implemented in the finite element code for non-linear structural analyses NOSA, entirely developed by the members of the Laboratory. The NOSA code has been successfully applied to a number of engineering problems.

Staff members
Roberto Scopigno is a Research Director with CNR-ISTI. He graduated in Computer Science at the University of Pisa in 1984. He has been engaged in research projects concerned with scientific visualisation, volume rendering, multi-resolution data modelling and rendering, 3D range scanning, Cultural Heritage applications; Roberto is the CNR-ISTI responsible for the projects: EU PASR-2004 "CRIMSON: the Crisis Simulation System" and IST FET "CROSSMOD". Roberto is Vice-Chair of the Eurographics Association, Editor in Chief of the Computer Graphics Forum journal and member of several IPCs of international conferences.

Cristina Padovani is a Research Director, Head of the Mechanics of Materials and Structures Laboratory, Research interests: constitutive response of materials, with particular emphasis on non-linear elastic and masonry materials; study and numerical solution of equilibrium and evolution problems in continuum mechanics; in

particular, statics and dynamics of masonry solids. Currently involved in research projects concerned with the numerical modelling of the mechanical behaviour of masonry buildings.

Recent publications

G. Impoco, P. Cignoni, R. Scopigno "A six-degrees-of-freedom planning algorithm for the acquisition of complex surfaces ", International Journal of Shape Modeling, vol. 11(1), June 2005, pp. 1-23.

Paolo Pingi, Andrea Fasano, Paolo Cignoni, Claudio Montani, Roberto Scopigno, "Exploiting the scanning sequence for automatic registration of large sets of range maps", Computer Graphics Forum, NCC Blackwell, Vol. 24(3), 2005, pp.517-526.

M. Callieri, P. Cignoni, R. Scopigno, G. Gori, M. Risaliti "Beyond manual drafting: a restoration-oriented system", Int. Jour. Cultural Heritage, Elsevier., vol. 7(4), 2006, pp. (in press)

T. Franken, P. Cignoni, M. Dellepiane, F. Ganovelli, C. Montani, R. Scopigno, "Minimizing user intervention in registering 2D images to 3D models", The Visual Computer , Springer, vol. 21(8-10), 2005, pp.619-628.

M. Callieri, P. Debevec, J. Pair, R. Scopigno "A Realtime Immersive Application with Realistic Lighting: the Parthenon", Computer and Graphics, Elsevier, Vol. 30 (3), 2006, pp. 368--376.

Bernardeschi K. Padovani C., Pasquinelli G., "Numerical modelling of the structural behaviour of Buti's bell tower" Journal of Cultural Heritage 5(4), pp. 371-378, 2004.

Degl'Innocenti S., Padovani C., "A numerical method for the limit analysis of masonry structures" Structural Engineering and Mechanics 18(1), pp. 1-20, 2004.

Degl'Innocenti S., Padovani C., Pasquinelli G., "Numerical methods for the dynamic analysis of masonry structures" Structural Engineering and Mechanics 22(1), pp. 107-130, 2006.

CNR-IA

The **Institute of Acoustics *"O.M. Corbino*" – IA** is the only Research Centre in Italy entirely devoted to Acoustics. The Institute, established in 1936, is one of the oldest Institute of the **Italian National Research Council** (**C.N.R.**). The research activities of the Institute are in the following fields:

- Environmental Acoustics.
- Physical Techniques for Cultural Heritage.
- Underwater Acoustics – SIT Calibration Centre N° 194
- Acoustic Emission – Ultrasonic Testing.
- SAW & BAW acousto-opto-electronic microdevices and Sensors.

The IA has a long tradition of research in all the major branches of Acoustics: materials and devices, transducers and sensors for environmental acoustics, physical technologies for the safeguard of Cultural Heritage, geoacoustics, underwater acoustics and technologies for monitoring materials degradation, studies and applications to climate and environment.

The Institute of Acoustics has a well established tradition in investigations dedicated to the Cultural Heritage safeguard. Since its foundation, the Institute began this branch studying the acoustic quality of antique violins and other musical instruments. In the 70s, the IA was involved in particular projects in this field, extending the activity to the study of the acoustical vibration produced by sound sources placed in site where artistic manufacts were located, for the evaluation of damage to works of art. An example is the investigation performed on the vibrations induced by the organ sound on the "Christ" of Cimabue and other frescoes in the Church of S. Domenico in Arezzo.

- European Project: EU Populus Project Human Capital and Mobility on the subject "Non Destructive Techniques Applied to Landscape Archaeology";
- CNR Strategic Project "Technologies of the Past and on the Past";
- Special Project on the Safeguard of Cultural Heritage of CNR.

The research activity of the group is focused on:

- "Nondestructive technique for the detection and mapping of detachments in frescos, by means of Acoustic Imaging ",
- "Acoustic-wave echographic technique for high-resolution for subsoil and underwater prospecting of archaeological remains".
- Study of acoustic behaviour of non homogeneous structures by means of Laser Vibrometry

Staff members:

Massimiliano Benetti was born in Venice, Italy, on June 21, 1970. Since 2006, he works for the Italian National Council of Researches (CNR) at the Institute of Acoustics "*O. M. Corbino*", on electro-acoustic chemical and physical sensors mainly devoted to the monitoring of natural environment. In 2006 he received the Ph.D. degree in Microsystems Engineering from University of Rome Tor Vergata, defending a thesis entitled: "Design and implementation of surface acoustic waves micro-sensors applied to multi-sensing systems and wireless applications". Main areas of expertise and interest include surface and bulk acoustic waves devices, deposition and characterization of thin piezoelectric films, electronic oscillators and etc.

Paola Calicchia graduated in Physics in 1994. She worked for the Italian National Council of Researches (CNR) since her thesis at the Institute for Photonics and Nanotechnologies, first, and at the Institute of Acoustics "*O. M. Corbino* since 1998. Experience in the development of innovative methodologies and relative devices for many applications in the field of acoustical techniques applied to Cultural Heritage, diagnosis of detachments in frescoes, acoustic imaging, analysis of acoustic images for underwater prospecting, material characterization, semiconductor surface analysis, spectroscopic techniques, employment of Synchrotron Radiation. Since 2006 she is Quality Manager for the Calibration Centre SIT N.194.

Giovanni Bosco Cannelli graduated in Physics in 1966. He worked in different activities in the field of Physics: - Nuclear Physics at Electrosynchrotron of Frascati, Italy; - Meteorology at NATO Air Force Base "S.Damiano", North Italy, as Geophysicist Reserve Officer;- Technical Physics at Rome University "La Sapienza", as temporary Assistant Professor. In 1974, Cannelli was awarded by the National Academy of Lincei the prize for Physics, sponsored by the Italian Ministry of Public Instruction, for an innovative acoustic method which allowed, for the first time, the determination of some thermoelastic parameters in transition metals as a function of temperature. In 1977, he joined the Istituto di Acustica "O. M. Corbino", Italy, where he was Head of Environmental Acoustics Department for twenty years before receiving the appointment of Technology Director for Environmental Acoustics from the Italian National Research Council (CNR). Since February 2005 he is CNR Scientific collaborator. His present main research interests are in the field of acoustic technologies applied to environment and cultural heritage, such as diagnostic methodologies for frescoes conservation and archaeological subsoil and underwater prospetting.

Recent publications:

[1] M. Benetti, D. Cannatà, F. Di Pietrantonio, E. Verona, "*Growth Of AlN Piezoelectric Films on Diamond for High Frequency Surface Acoustic Wave (SAW) Devices*", IEEE Ultrasonics, Ferroelectrics and Frequency Control, UFFC-**52,** p. 1806 (2005).
[2] M. Benetti, D. Cannatà, F. Di Pietrantonio, V. Fedosov, E. Verona, "*Gigahertz-range Electro-Acoustic Devices Based on Pseudo-Surface-Acoustic-Wave in AlN/Diamond/Si Structures*", Applied Physics Letters, **87**, 0335041/3 (2005).
[3] M. Benetti, D. Cannatà, F. Di Pietrantonio, V. Foglietti, E. Verona, "*Microbalance Chemical Sensor based on Thin Film Bulk Acoustic Resonator*", Applied Physics Letters, **87**, 1735041/3 (2005). Selected for publication on the Virtual Journal of Nanoscale Science & Technologies, **12**, (2005). http:\\www.vjnano.org .
[4] M. Benetti, D. Cannatà, F. Di Pietrantonio, E. Verona, "*Advanced Saw Transducers for multisensing systems applied to low concentration of volatile compounds*", Proceedings of the AISEM, Ferrara (Italy), February 08 – 11, 2004.
[5] M. Benetti, D. Cannatà, A. D'Amico, F. Di Pietrantonio, V. Foglietti, E. Verona, "*Thin Film Bulk Acoustic Wave Resonator (TFBAR) Gas Sensor*", Proceedings of the IEEE International Ultrasonics Symposium, Montréal (Canada), August 23-27, 2004, p. 1581.
[6] G. B. Cannelli, P.Calicchia, "Metodo acustico non invasivo per la rivelazione e la mappatura dei distacchi nei dipinti ad affresco e nei dipinti murali in generale, e relativo apparecchio per la realizzazione di tale metodo" (Italian Patent N. RM 99 A000410, 25 june 1999; PCT N. PCT/IT00/00244 13 june 2000, USA Patent US 6728661 27 april 2004, European Patent EP1190243B1, 6 September 2006).
[7] Paola Calicchia, Giovanni Bosco Cannelli, "Detecting and mapping detachments in mural paintings by non-invasive acoustic techniques: measurements in antique sites in Rome and Florence", Journal of Cultural Heritage, vol. 6(2), 115-124, 2005.
[8] Calicchia P., Cannelli G. B. "*Revealing Surface Anomalies in Structures by in situ Measurement of Acoustic Energy Absorption*", Applied Acoustics vol.63/1 pp 43-59 (2002), Elsevier Science.

P2 – UPV-EHV
The University of the Basque Country, San Sebastian and Bilbao, Spain

The UPV/EHU will act within MACH as one partner although three groups with different research topics are involved in different Tasks:

1.- The group leaded by Dr. Santiago Sanchez-Beitia, working in the field of structural analysis
2.- The group leaded by Prof. José Maria Becerril, working in the field of biological affections and diagnosis
3.- The group leaded by Prof. Juan Manuel Madariaga, working in the field of chemical diagnosis and processes

The role of UPV (Faculty of Architecture) will be like leader of WP7 and participant in the others Work Packages.

In the WP7, UPV (Faculty of Architecture) will be the partner in charge to coordinate the technologies or methodologies that will be propose for their recommendations taking care of the following considerations:

1.- Innovating Character
2.- Problems to solve by each Standard proposed
3.- Relation with existing Standards
4.- State of development of each technique to be Standardised

UPV (Faculty of Architecture) will contact directly with RILEM, or other European agencies of Standardisation, in order to detect the necessary degree of development of the methods and techniques to be standardized. There exists the possibility to foresee some reduced number of tests in order to check totally the proposals of Standard.

In agreement with the previous experience developed in the Faculty of Architecture, UPV (Faculty of Architecture) will participate in Task 2.1 in the development of the following concepts:

Stylistic and Constructive identification
History and past interventions
State of conservation of the monument and morphology identification
Material and structural identification

UPV (Faculty of Architecture) will contribute to Task 5.2 developing the Hole Drilling Technique for on site measurements of stresses in the structural elements of Cultural Heritage Constructions. These experimental techniques will be used in Task 6.3 for on site measurement of stresses (non-residual) of selected monuments.

Partner UPV (Faculty of Architecture) will participate in the other WPs of transversal (horizontal) character, that is to say, in WP3, 4, 8, 9 and 10.

Staff members:

Dr. Santiago Sánchez-Beitia
Dr. Alberto Zulueta
Dr. Javier Barrallo
Prof. Juan José Anza

Recent publications

Schueremans, L., Sánchez-Beitia, S. The Hole Drilling Technique for On Site Deduction of the Stresses States in Stone Masonries by Using Eight Strain Gages. Materials and Structures Journal. Springer Ed. (2007, in revision).

Sánchez-Beitia, S. Stresses analysis in stone masonries by means of the Hole Drilling Technique: Laboratory tests and a Case Study. Experimental Techniques Journal (SEM-Society for Experimental Mechanics, 2007 in revision).

Schueremans, L. Vanbalen K, Sánchez-Beitia, S. On Site Stresses Analysis on the Piers of the Saint Jakobs Church in Leuven (Belgium). Construction and Buildings Materials Journal (2007 In revision).

Sánchez-Beitia S. Stress Analysis of the Piers of the Tarazona Cathedral (Zaragoza-Spain) by Means of the Hole-Drilling Technique. Construction and Buildings Materials Journal (2006). Elsevier Ed.

Sánchez Beitia S. Stresses analysis at the Altes Museum of Berlin by means of the Hole Drilling Technique. Construction and Buildings Materials Journal (2006). Elsevier Ed.

Sánchez-Beitia S. Book entitled "Análisis de Sistemas Portantes en Patrimonio Arquitectónico: Relación entre los elementos Constructivos y la Transmisión de Cargas". Txertoa Eds. San Sebastián , 2003 ISBN: 84-7148-383-1

Barrallo J, Zulueta A, Blanco L, Caro J, Sánchez-Beitia S. Stress measurements on ancient structures by the hole drilling method. Experimental Techniques Journal (SEM-Society for Experimental Mechanics) 1994; 19 (3): 9-13.

Barrallo J, Zulueta A, Sánchez-Beitia S. The Donostia Method for stress measurements in architectural heritage. STRAIN (Journal of British Society for Strain Measurement) 1999; 35 (3): 107-112

The group of **Plant Physiology** leaded by the Prof. José María Becerril is part of the Plant Biology and Ecology Department of the University of the Basque Country (Bilbao, Spain) and has the qualification of excellence since 2002. Last year the Faculty of Science and Technology, where the group works, has reached to the Silver Q award within the European System of Quality, leaded here by the Euskalit Organization.
The expertise of the group deals with biochemistry, physiology, ecophysiology of phototrophs and the stress effects caused by natural (light, temperature, waters relations) and antropic factors (organic and inorganic pollutants, biocides). The staff is skilled in different methodologies (chlorophyll fluorescence on site determination, spectroradiometry, HPLC, bioassays, Physiological profiles, Biolog system etc.) and some of them would be innovatively applied into these approaches.
The role of the group would deal with Task 5.2. to develop a innovatieve system toe stimate physiological profiles of biodeteriogens (Biolog fingerprint) on stone ansd validate in Task 74. These new developments together with other standar techniques .will be applied in Task 6.3 and 6.4 evaluating the aspect of biological damage in materials, caused by biodeteriogens and the influence of seasonality on monitoring and control. This knowledge will be used in WP8 to create a risk assessment model.

Staff members:
Prof. José María Becerril
Prof. Antonio Hernández
Prof. José I. García-Plazaola.
Oihana Barrutia
Raquel Esteban

Recent publications
-. Hormaetxe, K; Esteban, R.; Becerril, JM; & García-Plazaola JI. 2007. Pasticity of photoprotective mechanisms of B. sempervirens L. Leaves in response to extreme temperatures. Plant Biology 9: 59-68.
-. Hernandez-Allica, J.,Garbisu, C.; Barrutia, O., Becerril, J.M., , S.P.,.2007. EDTA-induced heavy metal accumulation and phytotoxicity in cardoon plants. Environmental & Experimental Botany 60: 26-32.
-. Santos, F., Hernandez, J., Becerril, J.M., Amaral-Sobrinho, N., Mazur, N., Garbisu, C., 2006. Chelate-induced phytoextraction of metal polluted soils with Brachiaria Decumbens. Chemosphere 65 (1), pp. 43-60
-. Hernandez-Allica, J., Becerril, J.M., Barrutia, O., García-Plazaola, J.I., Zhao, F.J., McGrath, S.P., 2006. Synthesis of low molecular weight thiols in response to Cd exposure in Thlaspi caerulescens. Plant Cell and Environment, 29 (7), pp. 1422-1429.
-. Hernández-Allica, J., Becerril, J.M., Zarate, O., Garbisu, C., 2006. Assesment of the efficiency of a metal phytoextraction process with biological indicators of soil health. Plant and Soil 281(1-2), pp. 147-158
-. Artetxe, U., Hernández, J., García-Plazaola, J.I., Becerril, J.M., 2006. Do light acclimatation mechanisms reduce the effects of light-dependent herbicides in duckweed (lemna minor)?. Weed Science, 54 (2), pp. 230-236
-. De María, N., Becerril, J.M., García-Plazaola, J.I., 2006. New insights on Glyphosate mode of action in nodular metabolism: Role of shikimate accumulation. Journal of Agricultural and Food Chemistry, 54 (7), pp. 2621-2628

The group of **Environmental Analytical Chemistry**, leaded by Prof. Juan Manuel Madariaga, was established in 1987 and is part of the Analytical Chemistry Department of the University of the Basque Country (Bilbao, Spain) and has the qualification of excellence since 2002. Last year the Faculty of Science and Technology, where the group works, has reached to the Silver Q award within the European System of Quality. The expertise of the group is in the field of environmental heritage, both natural and cultural, developing new diagnosis methodologies through the measurements of different pollutants using a multianalytical approach, most of then NDT devices and/or methodologies.
The role of the group would deal with Task 5.2 developing new low cost innovative NDT devices to extract ionic and non-polar chemicals from the surfaces and inner layers of stones and mortars. Then they will be validated in Task 7.2. These new developments, together with other standard analytical protocols based on portable/mobile instrumentation, will be applied in Task 6.3 and 6.4 evaluating both the affections and state of

conservation post-treatment, from the chemical reactivity point of view caused by environmental stressors. Seasonality dependence factors will be specially considered. This knowledge will help in Task 8.2 to assess the sources for risks on such heritages.
Partner UPV (Environmental Analytical Chemistry) will participate in the other WPs of transversal (horizontal) character, that is to say, in WP1, 3, 4, 9 and 10

Staff members:

Prof. Juan Manuel Madariaga	Prof. Luis Angel Fernández
Dr. Nestor Etxebarria	Dr. Mª Angeles Olazábal
Dr. Gorka Arana	Dr. Alberto de Diego
Dr. Olatz Zuloaga	Dr. Aresatz Usobiaga
Dr. Kepa Castro	Dr. Irantzu Martinez-Arkarazo

Recent publications

M. Pérez-Alonso, K. Castro, M. Alvarez and J.M. Madariaga, Scientific Analysis versus Restorer's Expertise for diagnosis prior to a restoration process: The case of Santa Maria Church (Hermo, Asturias, North of Spain), Analytica Chimica Acta, 524, 379-389, 2004

J. Larreta, I. Martinez-Arkarazo, J. Sanz, J.C. Raposo, I. Tueros, A. de Diego, L.A. Fernández and J.M. Madariaga, Mercury speciation by Hydride Generation Atomic Absorption Spectrometry after Ion Exchange Separation in a FIA System (FIA-IE-HG-ASS), RMZ-Materials and Geoenvironment, **vol. 51**, 1963-1967, 2004

A. Delgado, J. Sanz, R. Carrera, O. Zuloaga, A. de Diego and J.M. Madariaga, Simultaneous mercury and tin speciation in environmental samples by GC-MIP/AES after preconcentration by solid phase microextraction, Journal de Physique IV, 107, 1423-1423, 2004

I. Martínez-Arkarazo, M. Angulo, A. Usobiaga, L.A. Fernández and J.M. Madariaga, Protection of carbonaceous materials by formation of a superficial oxalate layer, in ***Heritage Protection. Construction Aspects*** (J. Radic, V. Rajcic and R. Zarnic eds.), pp. 174-179, Secon HDGK, Dubrovnik, 2006

M. Pérez-Alonso, K. Castro and J.M. Madariaga, Investigation of Degradation Mechanisms by Portable Raman Spectroscopy and Thermodynamic Speciation: the wall painting of Santa Maria de Lemoniz (Basque Country, North of Spain), Analytica Chimica Acta, 571, 121-128, 2006

A. Delgado, A. Prieto, O. Zuloaga, A. de Diego and J.M. Madariaga, Production of artefact methylmercury during the analysis of certified reference sediments: use of ionic exchange in the sample treatment step to minimise the problem, Analytica Chimica Acta, 582, 109-115, 2007

I. Martinez-Arkarazo, M. Angulo, L. Bartolomé, N. Etxebarria, M.A. Olazabal and J.M. Madariaga, An Integrated Analytical Approach to Diagnose the Conservation State of Building Materials of a Palace House in the Metropolitan Bilbao (Basque Country, North of Spain), Analytica Chimica Acta, 584, 350-359, 2007

K. Castro, M. Pérez-Alonso, M.D. Rodríguez-Laso, N. Etxebarria and J.M. Madariaga, Non-invasive and non-destructive micro-XRF and micro-Raman analysis of a decorative wallpaper from the beginning of the 19th century, Analytical and Bioanalytical Chemistry, 387, 847-860, 2007

P. Vandenabeele, K. Castro, M. Hargreaves, L. Moens, J.M. Madariaga and H.G.M. Edwards, Comparative Study of Mobile Raman Instrumentation for Art Analysis, Analytica Chimica Acta, 588, 108-116, 2007

P3 – KUL

Katholieke Universiteit Leuven, Belgium. The K.U.Leuven team is composed as follows:
The Raymond Lemaire International Centre for Conservation (RLICC) that is connected to and collaborates with BWK-MAT and ASRO-CAAD. The RLICC has more than 30 years of experience in educating international and interdisciplinary groups of students in the preservation of the built heritage and more than 20 years of research experience addressing preservation of architecture and architectural remains on archaeological sites; analysis, diagnosis and repair of structures of the architectural heritage; the use of three-dimensional techniques of documentation and dissemination in studying built heritage; three-dimensional digital information system for the documentation, representation and conservation of our architectural heritage; Integration of Iconographical databases of the built heritage in Flanders RLICC has been involved in research projects with conservation implementation in Ecuador, Turkey, Syria, France and in Belgium and has a long standing tradition of collaboration with Monumentenwacht Vlaanderen (SC2).

Civil Engineering department, the Building Materials and Building Technology Division (BWK-MAT) has a developed multiple research activities addressing technical issues for conservation. It has been involved in various EC projects dealing with elaboration of the masonry damage diagnostic system and the damage atlas for ancient brick structures, with research on environmental damage on mortars, with research on mortar and pointing. Research on historical masonry technologies with in-depth insight in the behaviour of masonry with lime mortar as well as research on probabilistic evaluation of unreinforced masonry structures with a particular interest in historic masonry is supported by different regional science funding organisations. This group is actually coordinating activities that aim at funnelling research to eventually contributing to preventive conservation and to maintenance and monitoring based preservation strategies, such as with the European Commission in the SPRECOMAH project (www.sprecomah.eu).
Architectural and Urban planning department, Computer aided architectural design lab (ASRO.CAAD) has strong links with the research group in the same department on architectural history and on theory of preservation. In the field of heritage the research group has been collaborating with RLICC on research projects dealing with the use of three-dimensional techniques of documentation and dissemination in the study of the built heritage and on three-dimensional digital information system for the documentation, representation and conservation of our architectural heritage. Ongoing research is investigating the integration of photogrammetry and laser scanning, and to improve 3D-heritage documentation.

Staff members:
Koen Van Balen, prof. dr. ir.-arch, has a degree in architecture, in architectural conservation and a Ph.D. in engineering. He focussed his activities on the preservation of historical structures and on the understanding of the behaviour of ancient materials and building technologies. He is professor in building materials and their preservation. His research concerns technical aspects in conservation embedded in conservation methodologies for the architectural heritage.
Luc Schueremans, prof. dr. ir., graduated as a civil engineer at K.U.Leuven in 1995. He defended his Ph.D. thesis at the end of 2001, entitled "Probabilistic evaluation of structural unreinforced masonry". From 2002-2006, he was a post-doctoral researcher at the Building Materials and Building Technology Division of K.U.Leuven, Belgium, on a grant from IWT-Vl. Since 2006, he is a 20% part time associate professor at the Civil Engineering Department and 80% scientific collaborator at BWK-MAT;
Dionys Van Gemert, prof. dr. ir., is professor of building materials science and renovation of constructions at BWK-MAT. He is head of the Reyntjens Laboratory for Materials Testing. His research concerns repairing and strengthening of constructions, deterioration and protection of building materials, concrete polymer composites.
Herman Neuckermans, prof. dr. ir.-arch., is professor in architectural design theory, design methology and cognition at the department of ASRO. He is head of the CAADLAB division. His research activities focus on the use of computers in the early stage of design.
Björn Van Genechten: ir.-arch.,. He also has a post-graduate degree in air- and space technology and geographical information systems. He started as a researcher at ASRO-CAAD. His research focuses on the integration of photogrammetry and laser scanning especially in the field of cultural heritage documentation.

K.U.Leuven will contribute to:

- WP1: contribute to overall management of the project;
- WP2: P3-KUL is coordinator of WP2. It will support set-up of an integrated methodology of different surveying techniques at test site; develop 3D model of surveyed construction to attach and display information coming from database developed in WP4 allowing for integration of time dependency of information (4^{th} dimension); strategy for test site will be implemented based on preliminary research on local monument (Sint Jacobs church, Leuven);
- WP4: collaborate on interface between databases with results from various monitoring testing methods with the 4D surveyed and representation model of the test buildings; identify the mutual adaptations, assure possibility of timeline creation (=monitoring);
- WP5: on site damage and monitoring techniques related with stability problems (non earthquake related) based on optical sensors will be investigated, starting on test case of Sint-Jacobs church in Leuven to

allow for comparison with previous collected data; implementation of advanced diagnostic system in joint test case site.

- WP6: test application and further development of monument diagnostic system is carried out in collaboration with TNO (MWVl and MWNl: a mixed inspection team from both countries will be send to joint test case to carry out inspection); creating a platform on existing experience for the project clarifying the need for further developments and guiding the research activities. Structural diagnosis including the influence of foundations and underground; results on test case in Leuven will assure validation and effective use of techniques in the joint test case of Ortigia;
- WP8: contribution in discrete models for the finite element analysis of the selected monument; focussing on specific numerical modelling or applicability of general numerical models for historical structures. Parameter identification for probabilistic risk assessment has to be extended. Innovative research is to be performed into a probabilistic material model for masonry compressive strength, based on strength values of brick/stones and mortar and of other determining material parameters.
- WP9: Contribute to the construction of the Decision Supporting Tool (DST) in close exchange with Monumentenwacht (subcontractor of K.U.Leuven and of TNO) as critical stakeholders. KULeuven input is based on its previous experience with the development of the MDDS, which in its last phase has been improved within the EU project COMPASS. The development will be generated as a co-operation between TNO and KU Leuven as scientific partners, Monument Watch NL and Flanders as end-user partners in the project and finally two sme's involved in the software development as subcontractors of TNO (Thinkworks and SNA).
- WP10: K.U.Leuven will contribute to the dissemination of the results of the project at various stages of its development; it can also assure good contacts with many types of possible stakeholders.

Recent publications

Schueremans L., "Assessing the safety of existing structures using a reliability based framework: possibilities and limitations", International Journal of Restoration of Buildings and Monuments, Vol.12, No.1, pp. 65-79, 2006.

Schueremans L., Van Gemert D., "Benefit of Splines and Neural Networks in simulation based structural reliability analysis", Internationl Journal of Structural Safety, Vol. 27, Issue. 3, July 2005, pp. 246-261.

Schueremans L., Van Gemert D., Giessler S. "Chloride penetration in RC-structures in marine environment – long term assessment of a preventive hydrophobic treatment", Constr. and Building Materials, Vol. 21 (6), 2007, 1238-1249

Schueremans Luc, Van Gemert Dionys, "Kriging as an alternative for increased predictive power of meta-models in structural reliability", International Journal of Materials and Structural Reliability, Vol. 4 (2) , 185-198, 2006.

Luc Schueremans, Koenraad Van Balen, Kris Brosens, Dionys Van Gemert, Pierre Smars, "Church of Saint-James at Leuven (B) – structural assessment and consolidation measures", International Journal of Architectural Heritage, ed. Paulo Lourenço, Pere Roca, Vol. 1, pp. 83-108, 2007.

Schueremans L., Van Gemert D. "Using splines in reliability analysis", invited contribution to the "Computationally Intensive Methods" section of the Wiley Encyclopedia of Statistics in Quality and Reliability, November 2006.

Genechten B. and Neuckermans H., "Fusing laser scanning and photogrammetry creating close range architectural orthoimages", Augmented Heritage, proceedings of the 10th EuropIA international Conference, Sep 2005, p.35-44, ISBN 2-909285-32-4, Damascus, Syria, 13-15/09/2005;

Van Genechten B. and Neuckermans H., "Fusing laser derived DSM's and matched image edges to create close range ortho-images", Proceedings of the 11th International conference on Virtual Systems and multimedia (VSMM2005), Oct 2005, p. 473-480; Edited by: Hal Thwaites, ISBN 963 8046 63 5, Ghent, Belgium, 3-7/10/2005;

P4 TUC - Chania, Greece

Technical University of Crete, Greece

The Technical University of Crete is a new Institution founded in Chania in 1977 and accepted its first students in 1984. The purpose of this Institution is to teach and train engineers, to conduct research, to establish firm links with other academic Institutions and Industry both in Greece and EU and most importantly to function as the technological nucleus for the development of this region. The Institution provides excellent opportunities for developmental actions, encourages and supports its staff and faculty to assume leadership in such coordinated actions. The Laboratory of Mine Design, founded in 1997, will provide to the project a fully operational MTS-815 closed-loop servo-controlled testing

machine for rocks, an upgraded Drilling Resistance Measurement System (DRMS) and home-made as well commercial software for continuum and particle mechanics modeling FLAC, 3DEC, UDEC and PFC of Itasca. It supports a number of funded projects in the area of rock mechanics and rock modelling. Coordination of EC Projects SMT FP4 Project "Monuments", of Energy, Environment & Sustainable Development Project FP5 "DIAS" Established cooperation with monuments authorities in Greece for benchmark case studies in the MACH Project.

TUC will contribute to the following WP's and Tasks:
WP1: Contribution to overall management of the project;
WP4: Creation of internet based relational MACH Platform and databases in Java with graphics with the capability to be linked to "intelligent systems" (i.e. data mining, neural networks, expert systems).
WP5: In Task 5.2 Software development for microdrilling and indentation tools and execution of lab and in situ tests with these tools.
WP8: Coordination of the work package. Distinct Element (DEM) (2D & 3D) simulations, constitutive model advisor for damageable materials and stones in monuments.
TUC will also participate in the other WPs of transversal (horizontal) character, that is to say, in WP3, 9 and 10.

Staff members:
George E. Exadaktylos
Professor, Department of Mineral Resources Engineering, Technical University of Crete, Greece, Member of CEN/TC 246 WG 2 (Natural Stones), Affiliate Member of the "Porous Media Research Institution" - University of Waterloo (Canada), member of TC-34 International Society of Soil Mechanics, and author of more than 50 papers in refereed international Journals, and author of one book. Expertise in: Rock Fracture Mechanics, Rock Mechanics, Experimental Mechanics, Computational Mechanics.

Recent publications

1. Stavropoulou M.C., Giannakopoulos, K. and Exadaktylos G.E. (2005)., A theoretical and experimental study of rock cutting *J. Mech. Behavior of Materials*. Vol. 16, Nos 1-2, pp. 131-150.
2. G. Exadaktylos (2005), Freezing-Thawing Model for Soils and Rocks, *Journal of Materials in Civil Engineering (ASCE)*, "Special Edition on "Advances in Physico-chemical Stabilization of Geomaterials", Vol. 18, No. 2, March/April 2006, pp. 241-249.
3. Liolios P.A. and Exadaktylos G.E. (2006) A solution of steady-state fluid flow in multiply fractures isotropic porous media, *Int. Journal Solids Structures*, 43, pp. 3960-3982.
4. G. E. Exadaktylos (2006), Nonlinear rock mechanics, *Chapter 5, Part 1: The Universality of nonclassical nonlinearity*, THE UNIVERSALITY OF NONCLASSICAL NONLINEARITY WITH APPLICATIONS TO NDE AND ULTRASONICS, (P.P. Delsanto, Editor), 2006, XXII, 546 p., Springer, Hardcover, ISBN: 0-387-33860-8.
5. S.K. Kourkoulis, I. Prassianakis, Z. Agioutantis, G.E. Exadaktylos (2006), Reliability assessment of the NDT results for the internal damage of marble specimens, *International Journal of Materials and Product Technology*, Vol. 26, Number 1-2, pp. 35 - 56
6. G. Exadaktylos, S. Tsouvala, P. Liolios and G. Barakos (2006), A Three-dimensional Model of an Underground Excavation and Comparison with *in situ* Measurements, *Int. J. Numer. Anal. Meth. Geomech.*, 2006; 28:1533–1541, in print.
7. M. Stavropoulou, G. Exadaktylos and G. Saratsis (2006), A Combined Three-Dimensional Geological-Geostatistical-Numerical Model of Underground Excavations in Rock, *Rock Mechanics & Rock Engineering*, Springer-Verlag, pp. 31, in print.
8. G. Beer and G. Exadaktylos, Consideration of geological conditions in numerical simulation, Guimares, *Key Note Lecture*, In 5th International Workshop on Applications of Computational Mechanics in Geotechnical Engineering, University of Minho,Guimarães,Portugal,http://www.civil.uminho.pt/eventos/5wacmge/lecturers.htm
9. G. Exadaktylos & I. Vardoulakis (Editors), *Bifurcation, Instabilities and Degradation in Geomechanics*, Springer, 2006, February 2007, pp. 480.

P5 – SINT

SINT Technology Srl

SINT Technology Srl was founded in 1990 and it has a staff of over 25 persons. Mainly they are graduate engineers who are all trained and qualified in measurement, analysis and diagnostics and mechanical, electronic and software design engineering.
The company carries out mechanical and electronic design and develops the software necessary for the realization of the prototypes of new machines and tests stands. It conducts research and development for small and-medium-sized companies in the mechanical sector, with the objective of development of new products and new production processes.
SINT Technology's main business activities are:
- Laboratory measurement, testing, analysis and diagnostic services applied to stress, vibration, noise, emissions and the thermodynamic performance of machinery and plants
- Production of measuring equipment for special applications, including metal and stone materials, and metal and stone works of art. In particular, the company produces the automatic system for measurement of residual stress RESTAN (Residual Stress Analyzer), that allows easy and complete control of residual stress tests by the hole-drilling strain gage method. Another product, the DRMS Cordless (Drilling Resistance Measurement System) is a measurement system designed to measure the drilling resistance of stone materials (stone and marble) and mortars
- Mechanical and electronic design engineering, construction and supply of special equipment. Design engineering and production of software for various applications: as an integral part of measuring equipment produced by SINT Technology, for acquisition of laboratory data, and for custom-design computer programs
- Training: SINT Technology is recognized by CICPND, the Italian Coordination Center for Nondestructive Testing, for providing first and second-level certification training courses and examinations for strain gage testing engineers
- Subsidized Research: consulting services for small and medium sized enterprises concerning research and development of innovation in technology and access to subsidies authorized under Italian law for technology innovation. In this connection, SINT Technology is one of the laboratories included by the Ministry of Education, Universities and Research (MIUR) in the register of highly qualified laboratories authorized to conduct research for small and medium sized enterprises.

SINT Technology was involved as a partner in the following European Projects:
- Hardrock (Contract SMT-CT96-2065), Development of a new measurement method to determine the superficial hardness of exposed monumental rocks.
- DIAS (Contract DIAS-EVK4-CT-2002-00080), Integrated Tool for in situ characterization of Effectiveness and durability of conservation techniques in historical structures

SINT Technology has the following patents:
- System for the execution of precision drilling, usable for the measure of the residual stresses by the blind hole drilling method. Patent N.FI91A 186
- Device for the measurement of the drilling resistance. Patent FI2005A000063

Since 1998 SINT Technology's quality management system has conformed to the requirements of standard UNI EN ISO 9001 for the following applications: *"Mechanical, electronic and software design engineering for prototypes of new machines; design and construction of test facilities and data acquisition systems; noise level, vibration, turbomachinery performance and strain gage measurement services"*.

Contribution of SINT to the MACH Project

The involvement of SINT is addressed principally in the WPs 5, 6 .
The main tasks will be to develop the prototypes of the following systems (WP 5):
a) equipment capable to measure onsite stresses in masonry blocks, masonry bricks and stone materials by using the hole drilling strain gauge technique and the deep-hole drilling technique.
b) an acoustic energy absorption diagnostic device for the evaluation of the degradation of frescoes.

Furthermore SINT Technology will collaborate to the development of the following test procedure (WP 7): "Test Method for the on site stress measurements on Stone materials, using the Hole drilling technique"
SINT will participate in the other WPs of transversal (horizontal) character, that is to say, in WP1, 9 and 10.

Staff members

Emilio Valentini

Doctor in Mechanical Engineering. Founder and Director of SINT Technology srl.
Senior Scientist, with more than 25 years of experience on the study of technical and scientific problematic related to measurement technologies for industry and cultural heritage applications.
Expert Evaluator for the EC in the FP6 – Specific Programme – Integrating & Strengthening The European Research Area Priority 8 5th Call for Proposals (SSP- 5A)
Luca Santucci
Doctor in Mechanical Engineering – Expert in Acoustics and Equipment Design and Equipment Design
Marco Fiaschi
Doctor in Mechanical Engineering – Expert in Vibration Analysis and Equipment Design
Alessandro Luzzi
Doctor in Computer Science Engineering - Expert in Data acquisition
Stefano Roccabianca
Doctor in Computer Science Engineering - Expert in Data acquisition
Alessio Benincasa
Doctor in Managerial Engineering – Assistant in Project Management

Recent publications

E.Valentini, D.Vangi - Un sistema automatico per la misura delle tensioni residue con il metodo del foro cieco *(An automatic system for measuring of residual stress by the blind hole drilling method*) - XXI Convegno Nazionale Associazione Italiana per l'Analisi delle Sollecitazioni (AIAS), Genova September 23-26, 1992

E.Valentini, D.Vangi - Procedura di prova ed errori di misura nella analisi delle tensioni residue nello spessore con il metodo della rosetta forata (*Test procedure and measurement errors for residual stress mearurement with the hole drilling method*) XXII Convegno Nazionale Associazione Italiana per l'Analisi delle Sollecitazioni (AIAS), Forlì October 6-9, 1993

E. Valentini - An automatic system for measuring non-uniform residual stress by the hole drilling method – Proceedings of the XIII IMEKO World Congress "From Measurement to Innovation", Torino September 5-9, 1994

A. Ajovalasit, G. Petrucci, M. Beghini, L. Bertini, D. Vangi, B. Zuccarello, E. Valentini - Analisi sperimentale delle tensioni residue con il metodo del foro (*Experimental analysis of the residual stresses by the hole drilling method*) - Associazione Italiana per l'Analisi delle Sollecitazioni (AIAS), Quaderno n. 3 "Studi per una proposta di Raccomandazione sulla Analisi sperimentale delle tensioni residue con il metodo del foro", March 1997

A. Ajovalasit, M. Beghini, L. Bertini, G. Petrucci, S. Ponticelli, W. Rosellini, D. Vangi, E. Valentini, B. Zuccarello - Confronto fra analisi di misure di tensioni residue variabili nello spessore condotte con la tecnica della rosetta forata (*Comparison between in-depth residual stress distributions obtained by the hole drilling method*) - Convegno Nazionale Associazione Italiana per l'Analisi delle Sollecitazioni (AIAS), Alghero September 12-15, 2001

P.Tiano, C.Filareto, S.Ponticelli, M.Ferrari, E.Valentini - Drilling force measurement system, a new standardisable methodology to determine the stone cohesion: Prototype design and validation - International Zeitschrift fur Bauinstandsetzen und Baudenkmalpflege 6. Jahrgang, Heft 2, 115-132 (2000)

G.Daurelio, V. La Tegola, C.Pappalettere, E.Valentini – Thin stainless steel sandwich structural panels all welded by laser technology: Residual Stresses Measurement by the Hole – Drilling Strain – Gage Method, XIII GCL – HPL 2000 International Symposium on Gas Flow & Chemical Lasers and High Power Laser Conference, Firenze September 18-22, 2000

E.Valentini, A. Benincasa, M. Baggiani, S. Brogelli - Evoluzione della tecnologia di foratura ad alta velocità per la valutazione delle tensioni residue con il metodo della forata (*Evolution of the high speed drilling for the residual stress*

measurements) - XXXIV Convegno Nazionale Associazione Italiana per l'Analisi delle Sollecitazioni (AIAS), Politecnico di Milano September 14-17, 2005.

E.Valentini, A. Benincasa, P. Lorenzi. Sviluppo di un sistema automatizzato di misura delle tensioni residue con il metodo della rosetta forata (*Recent development of an automatic system for measuring non-uniform residual stress by the hole drilling method*) – Giornata di Formazione e Addestramento Istituto Italiano della Saldatura (IIS), Milano April 6 2006.

E. Valentini , M. Beghini, L. Bertini, D. Urso, A. Benincasa – Banco prova a flessione per la determinazione delle incertezze associate alla misura delle tensioni residue con il metodo del foro (*Flexural test rig for the determination of the uncertainties associated to the hole drilling method*) - XXXV Convegno Nazionale Associazione Italiana per l'Analisi delle Sollecitazioni (AIAS), Ancona September 13-16, 2006.

P6 – SMARTEC
Smartec SA, Manno, Switzerland,

Smartec has a consolidated experience in the development and production of monitoring and data acquisition systems based on fiber optics and conventional sensors.
Smartec will contribute in the development of the low-cost, universal fiber optics reading unit (WP5) used for structural stationary monitoringand in the validation of the Probabilistic Risk Assessment Model applying a model-free statistical analysis on the acquired monitoring data, in order to extract novelty functions as possible indicators of changes in the structural behaviour (WP8).
Smartec Sa will participate in the other WPs of transversal (horizontal) character, that is to say, in WP1, 3, 7, 9 and 10.

Staff members:

Dr Daniele Inaudi (CTO)
He received a degree in physics at the Swiss Federal Institute of Technology in Zurich (ETHZ). His graduation work was centered on the theoretical and experimental study of the polarization state of the emission of external grating diode lasers and was prized with the ETHZ medal. In 1997 he obtained his Ph.D. in civil engineering at the Laboratory of Stress Analysis (IMAC) of the Swiss Federal Institute of Technology in Lausanne for his work on the development of a fiber optic deformation sensing system for civil engineering structural monitoring. Daniele Inaudi is co-founder and CTO of SMARTEC SA

Ing. Nicoletta Casanova (CEO)
Nicoletta Casanova received her degree in Civil Engineering at the Swiss Federal Institute of Technology in Zurich (ETHZ) in 1994. From 1994 to 1999 she was active as Technical Director at the Laboratory for material testing Istituto Meccanica dei Materiali SA (Grancia, Switzerland) and from 1994 to 1996 also as scientific co-worker at the Swiss Federal Institute of Technology in Lausanne for the development of a fibre optic deformation sensing system for civil engineering structural monitoring. Since 1996 she is cofounder, director and president of SMARTEC SA. From 2000 to 2003 she was also director of the Laboratory Istituto Meccanica dei Materiali SA.

Ing. Luca Manettti (Project Engineer)
He took his degree in Rural Engineering and Geodesy at the Swiss Federal Institute of Technology Zürich in 1997. In 1999 joined the University of Applied Sciences of Southern Switzerland (SUPSI), leading the Navigation - Telemetry and Orientation group at the school's Computer Integrated Manufacturing Institute (ICIMSI), supervising students and directing industry-sponsored research and development programs. In 2001 co-founded the company GEODEV Earth Technologies, as a spin-off of a research project. Luca specialized in navigation applications, precise positioning with GPS and Geographic Information Systems and brings a deep knowledge in surveying and land management activities, as well as a qualified experience in leading projects and R&D teams.

Recent publications

Field testing and application of fiber optic displacement sensors in civil structures – D. Inaudi, 12th Int. Conference on OFS'97- Opical Fiber Sensors, Williamsbourg, invited paper, OSA (1977), vol 16. 596-599.
"Photonic sensing technology in civil engineering applications", D. Inaudi, Handbook of optical fibre sensing technology, J. M. Lopez-Higuera editor, Wiley'(2002), Wiley.
"Long-gage fiber optic sensors for structural monitoring", D. Inaudi, Photomechanics, P.K. Rastogi editor, Springer'(2000), p 273-293.
"Fiber optic sensor network for the monitoring of civil engineering structures", D. Inaudi, EPFL, Lausanne, Switzerland'(1997), Ph.D. Thesis No. 1612.

P7 – INNOWEP
INNOWEP GmbH, Wuerzburg, Germany

Innowep GmbH is a small German company working in the field of structural, visual, topographical and functional evaluation of materials and surface properties. For these tasks Innowep is developing and producing special measuring instruments but is also doing contract and free research and development. All relevant methods and techniques are patent protected. Innowep took part in EU-projects like CRAFT, HISTOCLEAN and takes part project VAC.
Innowep will contribute ton the project in WP 5 with the development of a fully mobile portable device for on site monitoring of 3D-topography and roughnesses in x-, y- and free direction and the visual impression (pattern documentation and analysis). This new diagnostic tool will be used in WP6. Innowep will participate in the other WPs of transversal (horizontal) character, that is to say, in WP1, 7, 9 and 10.

Staff members:
Wolfgang P. Weinhold
Jens Gräwe
Carsten Diegelmann
Michael Lysyy
Alexander Reykovski

Recent publications:
W. P. Weinhold, A. Wortmann, C. Diegelmann, E. Pummer, N. Pascua, Th. Brennan, R. Burkhardt, L. Goretzki, OptoSurf®, Measurement Technology for Use on Surfaces of Historic Buildings and Monuments Cleaned by Laser, Conference Proceedings LACONA6, Vienna 2005, in press.
W. P. Weinhold, L. Goretzki, Cleaning Techniques for Historic Buildungs, ISBE Int. Society for Building Environment, Trinity College, Dublin, September 2003.
L. Goretzki, W. P. Weinhold, Characterization of weathered layers on mineral based building materials using a combination of microstructural analysis MISTAN® and SEM investigation, International Journal for Restauration of Buildings and Monuments, 2, 3, 1996, 223-242.

P8 – UPC
Universitat Politècnica De Catalunya, Department of Constructions Engineering

Universitat Politècnica de Catalunya (UPC), founded in 1971, is a technical university offering courses at any level (BS, MS and Ph.D.) in Engineering (Mechanical, Civil, Computer), Architecture, Applied mathematics, Economics and Health Sciences. Within the UPC, the Department of Construction Engineering (DEC) is deeply involved in education and research in the fields of construction materials and design, analysis, construction and maintenance of concrete, steel and masonry structures. During the last 4 years, the DEC has participated in more than 30 research projects funded by the Spanish Government or the European Commission and a similar number of projects funded by private companies. A significant part of these projects were related to the analysis, and conservation of architectural heritage (including ARQ2002-04659, *"Strength response and strengthening of*

masonry constructions subject to cyclic and dynamic actions [2003-2006] and BIA2006-04127 "*Experimental analysis and modelling of the response of masonry structures subjected to in-plane and out-of-plane loading*", funded by the Spanish Ministry of Science and Technology, and , Ecoleader – Lis 3 *"Rocking motion and impact of historical constructions"* [2003-2005], ALA/95/23/2003/077-122 *"Seismic Resistance of Cultural Heritage Buildings"* [2004-2006], TIP3-CT-2003-001653 *"Sustainable bridges – Assessment for future traffic demands and longer lives"* [2003-2007], funded by the European Commission.

UPC will coordinate WP 9 aimed at the development of a Decision Supporting Tool (DST) for the diagnosis and scheduled maintenance. Particularly, UPC will coordinate the process consisting of the integration all the information obtained from previous WP's with the purpose of damage characterization. Within the same WP, UPC will contribute to the identification of maintenance needs and the selection and validation of maintenance strategies which will be considered to formulate the DST . UPC will also contribute to assess the adequate application of state-of-art concepts, principles and practices oriented the conservation of monuments through its involvement in different work package. UPC will contribute with its experience on structural modeling and analysis by carrying out the analysis of one or more case studies by means of both classical (limit analysis) and non-linear FEM approaches within WP8.
Partner UPC will participate in the other WPs of transversal (horizontal) character, that is to say, in WP1, 2, 3, 7, 9 and 10.

Staff members

Prof. Pere Roca. His main activity is related to the analysis and conservation or strengthening of masonry buildings with focus on architectural heritage constructions and monuments. He has been responsible of 5 research projects funded by the Spanish Ministry of Science and Education and has collaborated in 3 different European research projects. He has published more than 100 papers in scientific or technical journals and conference proceedings. He is co-editor of *the Int. Journal of Architectural Heritage: Conservation, Analysis and Restoration* published by Taylor & Francis. He is the president of ICOMOS / ISCARSAH international scientific committee on structural analysis and restoration of historical structures since 2005. He has been organizer or co-organizer of 1st, 2nd International Seminar on Structural Analysis of Historical Structures (Barcelona, 1995, 1998), the 3rd, 4th and 5th International Seminar on Structural Analysis of Historical Constructions. He has been consultant in over 40 case studies in Spanish monuments including churches and Gothic cathedrals, Medieval monasteries, Medieval masonry bridges and 20th c. heritage buildings, including some of Arch. Gaudí's works in Spain.
Prof. Antonio Aguado. His research focuses on the fields of construction materials, construction management and decision taking tools. Prof. Aguado has published more than 20 books on very different research issues and more than 200 papers in scientific and technical journals and conference proceedings.
Prof . José L. González is responsible of Graduate and Postgraduate courses on Restoration of Ancient Constructions. He has more than 30years of experience largely related to inspection, conservation and restoration of historical buildings, having been responsible of the restoration of a large number of ancient buildings. He has collaborated with Prof. P. Roca in several research projects funded by the Spanish Ministry of Science and Education.
Dr. Climent Molins has participated several research projects funded by the Spanish Ministry of Science and Education. He has been consultant in over 10 case studies in Spanish monuments including churches and Gothic Cathedrals Medieval, masonry bridges and 20th c. heritage buildings.

Recent publications

Roca, P., López-Almansa, F., Miquel, J., Hanganu A. Limit analysis of reinforced masonry vaults. Engineering Structures 29 431-439 (2007)
Andreu, A., Gil L., Roca, P. A new deformable catenary element for the analysis of cable net structures. Computers&Structures 84 (29-30) 1882-1890 (2006)
Oliveira, D. V., Lourenço, P. B., Roca, P. Cyclic behaviour of stone and brick masonry under uniaxial compressive loading. Materials and Structures, 39 (2) 219-227 (2006)

Roca, P. The study and restoration of historical constructions. From principles to practice. Structural Analysis of Historical Constructions. Vol. 1 9-24. MacMillan. New Delhi (2006)
Roca, P., Andreu, A., Gil, L. (2006) Limit analysis of masonry cosntructions by 3d funcular modeling. Structural Analysis of Historical Constructions. Vol. 2 1135-1142. MacMillan. New Delhi.
Clemente, R., Roca, P., Cervera, M. Bamage model with crack localization. Application to historical buildings. Structural Analysis of Historical Constructions. Vol 2 1125-1134. MacMillan. New Delhi.
Caselles, O., Martínez, G., Clapés, J., Roca, P., Canas , J. A. Non-destructive geophysical surveys for dynamic characterization of Mallorca Cathedral. Proceedings o the First European Conference on Earthquake Engineering and Seismology. Geneva (2006)
Martínez, G., Roca., P., Caselles, O., Clapés, J., Canas , J. A. Dynamic investigation and linear análisis of Mallorca Mallorca Cathedral. Proceedings of the First European Conference on Earthquake Engineering and Seismology. Geneva (2006)
Lourenço, P.B., Oliveira, D.V., Roca, P., Orduña, A., Dry joint stone masonry walls subjected to in-plane combined loading, J. Struct. Engrg., ASCE, 131(11), pp. 1665-1673 (2005)
Roca, P. Simplified models for the assessment of masonry shear walls. Construction and Building Materials, 20, pp. 229-238 (2005)

P9 – UNROMA1

Università di Roma 1, Roma, Italy

La Sapienza is the largest University in Italy and one of the oldest, with its 750 years of history. The scientific and educational involvement of Sapienza in the field of Cultural Heritage is one of the most active in Europe, with research fields spanning from evaluation and restoration of single monuments or of entire historical centres, especially in seismic zones. These efforts are carried out through the many joint activities between the Department of Structural Engineering and the School of Restoration, both located in the Faculty of Architecture Valle Giulia of Roma. These efforts recently resulted in the writing of the new Eurocode 8 Part 3 on Assessment and Strengthening of existing buildings, in the recently issued Italian seismic code and in the guidelines of the Ministry of Cultural Heritage.

The UNROMA1 will take part in the MACH project with the clear task of participating in the joint effort of applying the purposely developed DST to a specific historical site, the island of Ortigia in Sicily. The site encompasses most of the problems that can be found in historical monuments (WP2). Thus, in a first instance, the contribution of UNROMA1 shall be towards the development of a methodology aiming at standardizing the information collected from devices installed on a monument and to treat them within a single framework (WP4), which will be used as the starting point for the conception of the DST (WP9). In addition to that, the contribution of UNROMA1 shall regard the aspects of structural diagnostics (WP6), with special reference to the selection of parameters, methods and protocols. Finally, a contribution is also foreseen in the definition of methods suitable to define the level of structural safety (WP8), by means of either analytical or numerical methods, with emphasis on the seismic case. UNROMA1 will participate in the other WPs of transversal (horizontal) character, that is to say, in WP1, 3, 7, and 10.

Staff members:

Giorgio Monti, MS, PhD, is full Professor at the University of Roma since 2001 and belongs to the Dept. of Structural Engineering of the Faculty of Architecture Valle Giulia, where he teaches the courses of Structural Analysis and Restoration. He has a wide experience in several areas of restoration, of earthquake engineering and innovative strengthening techniques. He has contributed to the drafting of some Parts of Eurocode 8, especially to Part 3 related to Assessment and Strengthening of existing buildings, to the new Italian seismic code (OPCM 3431) and to the Instructions for strengthening existing buildings with innovative techniques of the Italian National Research Council. He has participated in a number of projects funded by the EU, in particular: the PREC8 (HCM Network), the ICONS (TMR Network), the NODISASTR (Environment), the SAFERR

(Assessment, running), the SPEAR (Rehabilitation, running), the EN-CORE (European Network of Excellence on innovative materials, running) programs.
Franco Braga, is full Professor at the University of Roma and belongs to the Dept. of Structural Engineering of the Faculty of Engineering, where he teaches Seismic Engineering. He has a long experience in earthquake engineering, both in design of new buildings and in assessment of existing ones, and has been one of the pioneers in Italy for the application of the innovative concepts of seismic isolation and dissipation. He has substantially contributed to the writing of the new Italian Seismic Code.
Marc'Antonio Liotta, PhD, is a research assistant at the Dept. of Structural Engineering of the Faculty of Architecture Valle Giulia, where he teaches the course of Structures.
Silvia Alessandri, PhD, is a research assistant at the Dept. of Structural Engineering of the Faculty of Architecture Valle Giulia, where she teaches the course of Historical Development of Theories and Techniques in Construction.
Luigi Sorrentino, PhD, is a research assistant at the Dept. of Structural Engineering of the Faculty of Architecture Valle Giulia, where he teaches the course of Materials.
Giuseppe Scalora, is a professional engineer who has extensively worked on Detailed Plans for various Municipalities in Italy. He is the author of a book on Restoration of Historical Urban Fabrics.

Recent publications

Sorrentino, L., Kunnath, S., Monti, G., Scalora, G. (2007). Seismically induced one-sided rocking response of unreinforced masonry façades. *Engineering Structures*, Elsevier (in print).
Sorrentino, L., Kunnath, S., Monti, G., Scalora, G. (2007). Non-linear static and dynamic analyses of one-sided rocking of unreinforced masonry façades. *USNCCM9 Mini-symposium on Computational Mechanics of Masonry Structures*, San Francisco, 23-26 July.
Sorrentino, L., Kunnath, S., Monti, G., Scalora, G. (2007). Un modello accoppiato nel piano-fuori del piano per valutare il ruolo del peso dei solai, del livello di immorsatura, della qualità muraria e dei muri di controvento sulla risposta sismica. *Proc. XII Convegno L'Ingegneria Sismica in Italia*, Pisa, 10-14 June.
Braga F., Monti G., Liberatore D., Scalora G. (2006). Survey and restoration: the case of the block between Vicolo II and Vicolo III at the Giudecca of Ortigia, Sicily. *Conference Structural Analysis of Historical Constructions* (SAHC 2006), New Delhi, India, Nov.
Braga F., Monti G., Scalora G. (2006). A conservation plan method for historical city centres. *Conference Structural Analysis of Historical Constructions* (SAHC 2006), New Delhi, India, Nov.
Braga F., Monti G., Scalora G. (2006). A method for urban restoration applied to Ortigia (Sicily, Italy). *FACH Conference on the Construction Aspects of Built Heritage Protection*, Cavtat, Croatia, 14-17 October.

P10 – ITAM
Institute of Theoretical and Applied Mechanics of the Academy of Sciences of the Czech Republic, Praha, Czech Republic

Institute of Theoretical and Applied Mechanics, Academy of Sciences of the Czech Republic, v.v.i. has been supported since 2000 as a European Centre of Excellence ARCCHIP (Advanced Research Centre for Cultural Heritage Interdisciplinary Projects) under 5th EC FP. It originated in 1921 as a research institute for testing of building materials and structures, continued since 1953-2006 as a governmental research institute and since January 2007 it exists as a public research institute (v.v.i.). About 30 research workers and 30 technicians in the Institute are engaged in problems relating mostly to civil and structural engineering. This research is supported by on average 25 national and international research grants per year. In the field of historic materials and structures the ongoing projects involve six EC 6th FP grants, one CULTURE 2000 grant a US-Czech project and two national grants. The Institute is located in Prague and has a detached laboratory ARCHISS in Telč – a World Heritage City.

ITAM contributes to the MACH project with a development of methodological directions for a repetitive evaluation of a state of preservation of an architectural heritage followed by a development of a database of construction and material characterisation for 3D GIS (WP2). ITAM is the leader of WP3 coordinating the elaboration of an overview of methods, devices and procedures applied for monitoring and diagnostics of

historic structures. Development and testing of sensors for monitoring of vibration effects and determination of the moisture content of the foundations in connection with monitoring of the pore water table pressure changes will be carried out in the WP6. The monitoring methods will be included into the MACH Platform (WP4). ITAM's experience with long term monitoring of several cultural heritage objects will be summarised in order to contribute to the selection of parameters, methods and protocols definitions. The contribution to the Decision Supporting Tool (DST) will involve evaluation of the impacts of different techniques and strategies on the cultural values of monuments, identification of parameters to be determined/monitored as preventive measures (on facades and timber frame roof structures), data on maintenance and repair costs based on specific case studies including also life cycle of materials and conservation/restoration interventions (WP9).
Partner ITAM will participate in the other WPs of transversal (horizontal) character, that is to say, in WP1, 3, 5, 7, and 10.

Staff members:

Jan Válek is Head of the Department of mechanics of particulate media and his research interests involve study of historic mortars and masonry. He participated in the ONSITEFORMASONRY EC 5th FP project and worked as Secretary of the European Conference on research into cultural heritage "SAUVEUR" supported from the 6th FP. In both projects he served as the Institute's contact person. Mr. Válek is a member of RILEM and is active in its Technical committee on Repair mortars for historic masonry.

Miloš F. Drdácký who is also involved in several EC projects. He is the Head of the ARCHISS unit specializes in failure analysis of historic materials and structures, monitoring of damage, testing of materials and structures. He is an expert in structural diagnostics and strengthening, and in the development of damage mitigation measures. He is a member of ICOMOS ISCARSAH and CIVVIH Scientific Committees, and founding member of the IASS WG "Historic structures". He has been further working in the RILEM Technical Committees on timber assessment and on historic masonry assessment and recently was the responsible team leader elaborating a report on the protection of cultural heritage from natural disasters for the European Parliament (January2007).

Stanislav Pospíšil is a vice-director of the Institute of Theoretical and Applied Mechanics, Czech Academy of Sciences, where he works at the Structural Dynamics Department. He lectures at the Department of Structural Mechanics at the Technical University in Ostrava. Mr. Pospisil has been working in the field of structural dynamics since 1992. He was a technical cooperator of three European projects: ECOEST2 ERB FMG ECT 950048 including three institutions, TMR Program, Action 2, Access to large scale facilities, Deptm. of Structural Testing, Bergamo, Italy; ECOLEADER 2001, Method Statement for Shaking-Table Investigation of Hydrodynamic Pressures Dams, Bristol, UK and ECOLEADER 2002, HPRI-199-CT-00046 (cooperation with ENEL Hydro, TU Dresden), Seismic performance of laminated timber frames, ENEL, Bergamo, Italy.

Jiří Bláha, specialized in typology and development of historic roof frames, surveys of historic structures (Chairman of the Czech Society for Building Archaeology Surveys) and dendrochronology. He represents ITAM ASCR, v.v.i. in the Culture 2000 Project focused on study of European roof timber frames and structures. He maintains a specialized internationally recognized website www.roofs.cz on historic roof frames and historic carpentry (EUREKA project). He collaborated in the EC projects NOAH'S ARK, PICTURE and CULTSTRAT.

Vladislava Herbstová specializes in the soil behaviour investigation focused mainly on problematic soils such as clayfills and unsaturated soils. She is about to finish her PhD research. She is a leader of the research project GAUK 6/2006/R which is dealing with mechanics of unsaturated soils and its application in engineering geology. Ms. Herbstová worked on the research project Investigation of shear strength of clayfill material at TU Dresden – Inst. für Geotechnik under DAAD funding in 2006.

Recent publications

Bláha J., Drdácký M., Pospíšil S. (2006) Failures of architectural heritage due to wind effects. In: Proceedings of Heritage, Weathering and Conservation HWC-2006 Madrid, 21-24 June 2006, Spain

Drdácký, M.: Structural and material health monitoring of historical objects Situation in the Czech Republic, in Proceedings „Sensing Issues in Civil Structural Health Monitoring“ (ed. F.Ansari), pp. 127-132, ISBN 1-4020-3660-4 (HB), Springer, Dordrecht, The Netherlands, 2005.
Drdácký, M.F.: Experimental approach to the analysis of historic timber and masonry structures, In Proceedings “Structural analysis of historical constructions”, P.B.Lourenço, P.Roca, C.Modena, S.Agrawal (eds.), Vol.1, ISBN 10: 1403-93155-0, Macmillan India Ltd., New Delhi 2007, pp.25-40, 2006.
Drdácký, M., Pospíšil S., (2003): Earthquake Resistance of Structures and Dynamic Response Using Large Facilities Experiments. In C.H. Loh, K.C. Tsai, V. Renda, J.F. Chai (eds.): Proceedings of the Joint NCREE/JRC Workshop, Taipei, R.O.C., November 2003, pp. 265-275.
Fischer O., Schenkova Z., Fischer C., Kottnauer P., Koudelka P.,Náprstek J., Pichl R., Pirner M., Pospíšil S., Schenk V., Urushadze S. (2003): Description of seismic excitation for the aim of safety assessment of structures. Acta Montana, Ser. AB, No. 12 (132), pp. 127-137.
Herbstová V., Boháč J., Herle I. (2007). Suction and collapse of lumpy spoilheaps in Northwestern Bohemia. Conf. on Mechanics of Unsaturated Soils, Weimar, Germany (in print).
Herbstová, V. and Boháč, J. (2005). Laboratory investigation of the collapsibility of a clayey spoil heap soil. In Proc. GEOPROB 2005 - Int. Conf. on Problematic Soils. Famagusta, Cyprus, Vol. 2., 715-722.
Herbstová, V., Mašín, D., a Boháč, J. (2005). Parameters for non-engineered colliery clayfills. In Proc. GEOPROB 2005 - Int. Conf. on Problematic Soils. Famagusta, Cyprus, Vol 1. 335-342.
Herle I., Herbstová V. (2006). Laboratory investigations of clayfills. XIII.Danube-European Conference on Geotechnical Engineering, Ljubljana, Slovenia, 61-64.
Hughes, JJ. and Válek, J., ‘Mortars in Historic Buildings. A Review of the Conservation, Technical and Scientific Literature’, Published by Historic Scotland, Edinburgh 2003, p.80, ISBN 1903570824
Kasal B., Pospisil S., Jirovský I., Heiduschke A., Drdácký M., Haller P. (2004): Seismic performance of laminated timber frames with fiber reinforced joints Earthquake Engineering and Structural Dynamics, 33:633-646.
Pospíšil S., Drdácký M., Slížková Z., Knotková D., Delpech P. (2006): Surface degradation of complex architectural form due to atmospheric pollution, In: Proceedings of Heritage, Weathering and Conservation HWC-2006 Madrid, 21-24 June 2006, Spain.
Slížková, Z. and Válek J., ‘Historic Materials and their Diagnostics in the Czech Republic: a State-of-the-Art Review’, (invited paper) in European Research on Cultural Heritage – State of the Art Studies (M. Drdácký, ed.), Vol.3., pp.25-36, ITAM, Prague 2004.
Válek, J., ‘Compatibility of new mortars with historic masonry, mortars, renders and plasters’, Proceedings of 11th International Conference on Built Heritage Conservation, Tusnad 23-29 March 2003, pp. 178-183.
Válek, J., Veiga, R., ‘Characterisation of Mechanical Properties of Historic Mortars – testing of irregular samples’, proceedings of Structural Studies, Repairs and Maintenance of Heritage Architecture IX (STREMAH) conference, Malta 2005, Edts. C.A. Brebbia, A. Torpiano, WIT press , 2005 pp. 365-374.
Zembaty Z., Kowalski M., Pospíšilil S. (2006):Dynamic identification and modal analysis of a reinforced concrete frame in successive states of damage, Engineering Structures,.Elsevier, vol.28, no.5, 2006, pp.668-681.

P11 – IPPT

IPPT – Institute of Fundamental Technological Research, Polish Academy of Sciences, Warszawa, POLAND

The Institute is one of the biggest scientific establishments of the Polish Academy of Sciences - it disposes of 162 highly qualified scientists (of whom 22 are full professors, 28 are associate professors with completed post doctoral programme, 6 senior researchers and 90 doctors). The main task of both the Academy and the Institute is to conduct high quality research in the areas which are the focus of the world's science. As the name of the Institute suggests, from the day of its establishment in 1953, it is and has always been focused on basic theoretical and experimental research in the area of technology. Over many years, the Institute has become the leading research establishment making a considerable contribution to numerous areas of science and technology, successfully promoting new trends of development and having a very good reputation in Poland and abroad.

The principal areas of scientific research conducted by the Institute include theoretical and experimental mechanics of materials, constructions and fluids, computational methods in mechanics, acoustoelectronics and application of ultrasounds in medicine, continuum physics, polymer physics, electromagnetic effects, applied information science, mechatronics and robotics, engineering and energy-saving pro-ecology oriented building.

During years 2002-2006 IPPT was awarded financial support for more than 80 national projects granted by State Committee for Scientific Research. Among various projects granted in previous years there was *Program research development and recording of strains and settlement of walls and pillars of St. John's Church in Gdańsk*, (1997-2000) Target Project, KBN Nr 7 T07E 010 96C/3049, State Committee for Scientific Research,

The Institute has an extensive experience in international co-operation particularly in the area of international Research and Technology Development projects (RTD), which resulted in establishing the EU National Contact Point for Research Programmes in the Institute, responsible for information and advisory support concerning participation of Polish researchers and enterprises in the Fifth, Sixth and currently also the Seventh EU Framework Programme. During last five years Institute participated in 29 EC R&D Projects (in 5FP and 6FP) and coordinated 2 Centres of Excellence.

Within the Sixth EU Framework Programme The Excellence Network KMM-NoE (Knowledge-based Multicomponent Materials for Durable and Safe Performance) was established and financed by the European Commission The principal goal thereof is to create a European structure (virtual institute) composed of prominent academic and research establishments, small and medium enterprises and large industry partners dealing with issues of multi-component materials designed for safe and durable structures operating in the conditions of extreme loads, such as: complex thermo-mechanical loading, impact loading, cyclic loading, large deformations, high strain rates, high temperature regimes, variable temperatures and aggressive chemical environment.

Role in the Project
WP2 - Selection of Monuments task and providing a Benchmark site of St. John's church in Gdańsk (north Poland). IPPT is coordinating WP6 and is involved in the application of Structural diagnostic tools and collaborates with SINT and UPV/EHU on development of Test method for the on-site stress measurement on masonry materials using hole drilling technique and will also contribute to the integration of micro-core testing method into a Compendium of MDT diagnostic tools. WP7 guidelines for on-site structural monitoring. IPPT will also be involved in WP1, 3, 4, 5, 7, 8, 9 and 10.

Staff members

Marek Skłodowski
Ph. D., Polish Academy of Sciences, Institute of Fundamental Technological Research. Expert in monitoring of historical structures, development of sensors and measurement methods, experimental stress analysis, testing of historical structural materials. His current position is Main Specialist in Dept. of Promotion and Industrial Collaboration. He was involved in three EC funded projects of the 4th and 5th FPs (Polish team leader). Member of ICOMOS, SEM, and Section of Experimental Mechanics of Committee of Mechanics of Polish Academy of Sciences.
Joanna Pinińska
Professor at Warsaw University, Faculty of Geology –since 1990 and Head of Department of Geomechanics since 1984. Member of the State Scientific Committe since 1994, MSc in Geology and MSc.Eng.(1961), PhD. (1968), DSc. (1976). She the Author of more than 100 publications, four monographs and over 50 expertises and projects. Among numerous supervised dissertations there were two PhD dissertations concerning protection of historical monuments in Egypt (Deir El-Bahari area, 1994-1997, and Luxor area, 1996-1999). Main research fields are: Engineering Geology and Environment Protection; Devastated Land Reclamation and Utilisation; Geotechnical Evaluation of Underground Vastes Deposition; Rocks properties (examination, deterioration). She and was Main Researcher in FP5 project.
Leszek Małyszko
Graduated from the Warsaw University of Technology, Faculty of Civil Engineering where he received his Ph.D. and D.Sc. degree (habilitation) in 2005. He is an associate professor at the Department of Geotechnology and Structural Mechanics, University in Olsztyn. He is author of two books (in Polish) and scientific publications in the field of masonry research.
Andrzej Domonik

MSc in geology (2001) and PhD (2006), is Assistant Prof. at Faculty of Geology, Warsaw University. His main scope of scientific activity are engineering and structural geology, rock mechanics, ultrasonic testing, development and application of innovative methods and techniques for the stone monuments, deterioration assessment as a background for further conservation, renovation and protective efforts. He participated in 4 National projects granted by State Committee for Scientific Research.
Paweł Łukaszewski,
MSc in geology (1987) and PhD (1996), is Assistant Prof. at Faculty of Geology, Warsaw University. His main scope of scientific activity are engineering geology, rock mechanics, ultrasonic testing and detrioration of rock properties. He participated in 8 National projects granted by State Committee for Scientific Research. and was Main Researcher in FP5 project.

Recent publications

Domonik A. Representation of joint surfaces of the Podhale flisch sandstone in research on strenght in selected exposures of the Podhale Basin. Przeglad Geologiczny, vol 51, nr 5, Warszawa 2003., 430-435.

Domonik A., Paleostress impact on the strength of rock massif. Conf.: Geotechnika i Budownictwo specjalne 2004, tom I, wyd. KGBiG AGH, Kraków s.45-51.

J. Pininska (co. - authors: Del Prete M.; Gostelov P.) The application of the historical surveys in landslide hazard prediction; 1992. 5 pp. 3. figs. Int. Symp. on Landslides. New Zealand.

J. Pininska (co. - author: Fattach el Banna A.Complex analysis of destructive, swelling agents in monuments of the Deir el Bahari, Egypt); 1995. p. 1240 - 1250. Proc. Coll. Mondanum. Brussels.

J. Pininska Crack growth in the postcritical path of deformation of sedimentary rocks.; 1995. p.111-118. Int. Conf. MJFR-2. (Vienna/Austria). Balkema. Rotterdam.

J. Pininska (co. - author: Fattach el Banna A.)The impact of swell properties on the Esna-Shale of the ancient Monuments of the Deir El Bahari - Egypt.; 1996. p. 212-222. Symp. on Geotechnical Engineering for the Preservation of Monuments and Historic Sites.(Napoli/Italy). University of Napoli, Federico II.

J. Pininska Some problems of the stress distribution on structural contacts in natural rocks bodies.; 1997. p. 73-79. I Symp.on mechanics of unhomogeneous materials. Szack/Ukraine. Lviv University.

J. Pininska The microfracturing in rocks against the simulation of fracturing in brittle materials.; 1997. p. 382-397.(abstract in English). Symp. Geotechnics and underground mining. (Szklarska Poreba, Poland).

J. Pininska (co.- author: Lukaszewski P.)Ultrasonic monitoring of the acid rain impact on building stones.; 1997. p.5-17. Int. Symp. Ground Chemistry Implications for Construction. (Brookfield/UK). Balkema. Rotterdam.

J. Pininska Mechanical and thermal weathering problems of the Maadi Town Temple, Fayoum, Egypt.; 1999. p. 1011-1014. Int. Congr. ISRM. (Paris/France). G.Voulle & P. Berest. Paris.

Skłodowski M., 2007, Quasi-non-destructive testing of historical structural materials using micro-cores, in *Structural Analysis of Historical Constructions, New Delhi 2006. P.B. Lourenço,P. Roca, C. Modena, S. Agraval (Eds) ,860-865, ISBN 972-8692-27-7*.

Skłodowski M., 2006, Micro-cores technology for testing of historical materials, in H*eritage Protection –Cconstruction Aspects, Cavtat 2006, J. Radić, V. Rajčić, R. Žarnić (Eds),205-211, ISBN 953-95428-1-2.*

SkłodowskI M., Compact Diagnostic Test: Outline of Historical Monuments testing Procedure, *IFTR Reports, 3/2006*

P12 BAM
Federal Institute for Materials Research and Testing, Berlin, GERMANY

The Federal Institute for Materials Research and Testing (Bundesanstalt für Materialforschung und -prüfung, BAM) is a technical and scientific superior federal institution under the authority of Federal Ministry of Economics. The task of BAM is to promote the development of German economy. Its responsibilities are in the interacting fields of Materials - Chemistry - Environment – Safety. BAM is involved in the interdependent and complementary activities:
Research and development - Testing, analysis, approvals - Consultation and information

The Division VIII.2 is engaged in non-destructive damage assessment and environmental measurement methods including non-destructive testing in civil engineering (NDT-CE). The multidisciplinary team focuses on determination of measuring parameters, which are relevant for the assessment of structures, damage and contaminations in the natural and built environment. They have great experience in the fields of structure assessment and documentation, ultrasonic echo technique, impact echo, radar, active infrared thermography, endoscopy, moisture measurement using microwave technique and TDR, multispectral laserscanner and laser induced breakdown spectroscopy (LIBS). The division participated in the following EC FP5 projects: SMARTRAD, ONSITEFORMASONRY, RUFUS, TAILSAFE. Current work is performed in the FP6 projects Sustainable Bridges, SAFERAIL and CHEF.

Role in the project

BAM will contribute to:
WP3 - Concepts and strategies of analysis based on more than 15 years of experience in development and application of NDT methods and combination of methods due to its experiences gained in ONSITEFORMASONRY and further European and national projects related to the assessment of historic buildings.
WP4 - Integration of BAM NDT Compendium into the MACH platform
WP5 - Development of an automated active thermography system including software for data analysis and image processing for the contact less detection of voids, delaminations and inhomogeneities in the near surface region, comparison to complementary methods.
WP6 - Development and application of microwave technology for moisture investigation, influence of salt content.
WP7 - Standardisation of NDT methods (radar, active thermography, strategies for moisture and salt analysis), involvement of RILEM TC SAM
WP10 as coordinator for the exploitation and dissemination of gained knowledge and innovation

Research staff

Dr. Christiane Maierhofer is a physicist and has more than 14 years experience in the development and application of non-destructive testing methods for historic masonry structures. She is head of the Working Group Electromagnetic Methods for the Assessment of Structures at BAM and is involved in several national and international committees: Leader of Sub-Committee Radar of DGZfP, Coordinator of WG1 of the Focus Area Cultural Heritage of the ECTP, coordinator of FACH of the German CTP, Secretary of RILEM TC SAM, member of RILEM TC INR. She was coordinator of the FP5 project ONSITEFORMASONRY and is coordinator of the FP6 project CHEF.

Dipl.-Ing. Christian Köpp**,** engineer for environmental techniques, has 8 years experience in architecture and facility management and is working since 6 years in the department “Non-destructive Damage Assessment and Environmental Measurement Methods” of BAM. He is responsible for the Quality Management of the department and has taken on the administrative coordination of the FP5 project ONSITEFORMASONRY.

Dipl.-Ing. Jens Wöstmann**,** engineer for mechanical engineering, is a specialist for the development, application and validation of microwave methods since more than 11 years. He has experience in the analysis of moisture content and distribution in masonry structures and has been involved in several national and European research projects at BAM (ONSITEFORMASONRY, SAFERAIL, Sustainable Bridges, etc).

Dipl.-Ing. Mathias Röllig**,** engineer for electrical engineering, is an expert on active thermography. He has a lot of experience in the application of this technique to systematic investigations in the laboratory and was involved in several case studies at historic masonry structures.

Dipl.-Ing. Boris Gräfe is a building engineer and a PhD student at BAM preparing his doctoral thesis upon the development and application of air coupled ultrasonic transducers. He has more than 4 years of experience in the development of ultrasonic systems and of software tools for data analysis.

Recent publications

Maierhofer, Ch. , B III Instandsetzung und Ertüchtigung von Mauerwerk, Teil 3: Zerstörungsfreie Prüfung zur Beurteilung von Mauerwerk , Mauerwerks-Kalender 2007, Berlin: Verlag Ernst und Sohn

Maierhofer, Ch., Köpp, Ch., Binda, L., Zanzi, L., Santiago, J. R., Knupfer, B., Johansson, B., Modena, C., da Porto, F., Marchisio, M., Gravina, F., Falci, M., Galvez Ruiz, J. C., Tomazevic, M., Bosiljkov, V., Hennen, Ch., ... (s. u.) , Projekt Report EUR 21696 EN - Onsiteformasonry project - On-Site investigation techniques for the structural evaluation of historic masonry buildings (2006) 141 sites , European Commission, Luxembourg: Office for Official Publications of the European Communities, Bruessels (2006) 141 pages

Maierhofer, Ch., Hamann, M., Hennen, Ch., Knupfer, B., Marchisio, M., da Proto, F., Binda, L. and L. Zanzi , Structural evaluation of historic walls and columns in the Altes Museum in Berlin using non-destructive testing methods , in: Modena, Lourenco and Roca {(eds.);} Proceedings of the 4th International Seminar on Structural Analysis of Historical Constructions, 10-13 November 2004, Padova, Italy, pp. 331-341

Maierhofer, Ch., Krause, M., Mielentz, F., Streicher, D., Milmann, B., Gardei, A., Kohl, Ch. and H. Wiggenhauser , Complementary application of radar, impact-echo and ultrasonics for testing concrete structures and metallic tendon ducts, in: Proceedings of 83rd Annual Meeting Transportation Research Board of the National Academies, 11.-15. January 2004, Washington, D.C., USA, Paper 04-2651 on CDROM

Maierhofer, Ch., Arndt, R., Röllig, M., Rieck, C., Wather, A., Scheel, H. and B. Hillemeier , Application of impulse-thermography for non-destructive assessment of concrete structures , Cement & Concrete Composites 28 (2006) 4, pp. 393-401

Maierhofer, Ch., Arndt, R., Borchardt, K., Hasenstab, A., Röllig, M. and J. Wöstmann , Structural assessment with radar and active thermography , in: Radic, J., Rajcic,, V., Zarnic, R. {(eds.);} Proceedings of the International Conference Cultural Heritage, The Construction Aspects of the Heritage Protection , Dubrovnik, Croatia, 14-17 October 2006, pp. 77-85

Maierhofer, Ch., Brink, A., Röllig, M. and H. Wiggenhauser , Quantitative impulse-thermography as non-destructive testing method in civil engineering - Experimental results and numerical simulations, Construction in Building Materials 19 (2005) 10, pp. 731-737

Maierhofer, Ch., Brink, A., Röllig, M. and H. Wiggenhauser , Detection of shallow voids in concrete structures with impulse thermography and radar, NDT & E INTERNATIONAL 36 (2003)4, pp. 257-263

Helmerich, R., Maierhofer, Ch., Röllig, M., Arndt, R. and J. Vielhaber , Bond quality survey of loaded RC-beams with CFRP-plate repair using impulse-thermography , in: Cruz, P., Frangopol, D. and L. Neves {(eds.);} Proceedings of IABMAS 2006 - Third International Conference on Bridge Maintenance, Safety, Management Life-Cycle Performance and Cost, 16.-19. Juli 2006, Porto, Portugal, Paper 105 on CD-ROM

Gräfe, B. and M. Krause , Basic investigation with air-coupled ultrasonic echo for concrete elements , in: Al-Quadi, I. and G. Washer {(eds.);} Proceedings of the NDE Conference on Civil Engineering, 14.-18. August 2006, St. Louis, MO, USA, pp. 480-487

P13 - TNO

TNO Built Environment and Geosciences, Delft, The Netherlands

TNO has been active in the field of conservation for more than 30 years. It is a private organization and its research includes the study of decay phenomena of building materials, measures against moisture- and salt-related problems and the effects of atmospheric pollution. This research is carried out for local and central authorities, restoration architects and building companies. TNO provides monitoring and diagnosis, restoration and maintenance advice and the implementation of treatments. The organization also participates in a program for the dissemination of information that was recently set up by the Netherlands Governmental Service for the Preservation of Monuments and Historic Buildings. It has been involved in several EC projects concerning the built cultural heritage, both as participant and as coordinator.
The role of TNO in the MACH project will consist in:

WP6 - On site investigation of deterioration phenomena and processes related to presence of salt and moisture and monitoring their behaviour in time.
WP8 - Assessment of risks related to conservation intervention
WP9 – Integration of the existing MDDS (Monument Damage Diagnostic System) into the MACH Platform together with two small SMEs as subcontractors: SNA and Thinkworks.
TNO will participate in the other WPs of transversal (horizontal) character, that is to say, in WP1, 2, 3, 4, 7, and 10.

Research staff
Rob van Hees, Professor of Conservation Technology at the Delft University of Technology, MSc in Building Physics and Building Technology, Senior Researcher and coordinator of the research group on monuments conservation at TNO Building and Construction. Main fields of interest, reflected in past and running research projects and research committee memberships, are durability of materials, conservation techniques and compatibility of new and old materials. He is member of research committees on lime mortars, façade cleaning, rising damp, consolidants and water repellent treatments. He is an active participant in various CIB, RILEM, IEA and WTA initiatives. He has ample experience in international co-operation projects and has been coordinator of several EU-funded projects (Surface treatments, Pointing, COMPASS) .

Dr. Barbara Lubelli, MSc. architect, experience in research on mortars and renders. She has a PhD on NaCl decay to porous building materials. She works in consulting projects on renders and on building pathology. Worked in EU projects like ASSET, COMPASS, Saltcontrol.
Also a subcontractor (SNA) having experience in the development and setting up of MDDS and Thinkworks (builder of the software behind MDDS) will be involved. Finally a very small (in terms of person months) involvement of Monument Watch in the Netherlands will act in a mirror group giving practical input.

Recent publications
R.P.J. van Hees, L. Binda, I. Papayianni and E. Toumbakari, *Characterisation and damage analysis of old mortars*, in Materials and Structures / Materiaux et Constructions, Vol 37, November 2004, pp 644-648
B. Lubelli, R.P.J. van Hees, C. Groot, The role of sea salts in the occurrence of different damage mechanisms and decay patterns of brick masonry, *Construction and Building Materials*, 18 (2), 2004, pp.119-124
R.P.J. van Hees, S. Naldini, *How to select a plaster for a salt loaded substrate. The use of an expert system for diagnosis and selection*, Proceedings ICOMOS workshop "Enduits degrades per les sels: pathologies et traitements" – Dossier technique no 6 - 2004, 14 Dec. 2004, Paris, 13p.
R.P.J. van Hees, S. Naldini & M. Sanders, *An expert system for analysis of damage to plasters due to salt and moisture*, in Proceedings Seminar 'Soluble salts in the walls of old buildings. Damages, processes and solutions', pp. 16.1-16.11, Lisbon, LNEC, 14-15 February 2005
Rob P.J. van Hees, Barbara Lubelli, Analysis of transport of salts in restoration plasters, in: European Research on Cultural Heritage – state of the art studies, eds. Stefan Simon & Milos Drdacky, Volume 5, ITAM, Prague 2006, pp. 315-327
B. Lubelli, R.P.J. van Hees, C.J.W.P. Groot, Sodium chloride crystallization in a salt transporting restoration plaster, *Cement and Concrete Research* **36** (8) 2006, pp. 1467-1474
B. Lubelli, *Sodium chloride damage to porous building materials*, Delft University of Technology, 2006, PhD thesis

P14 - UMINHO
Department of Civil Engineering of the University of Minho, Portugal

UMINHO is a young and dynamic department including 50 scholars, from which 30 hold a Ph.D. degree. The technical staff consists of 10 technicians. The department is responsible for a five-year graduation in Civil Engineering, three professional Master courses (Municipal Engineering – Majors in Urban Planning, Sanitary Engineering, and Roads; Civil Engineering – Majors in Structures and Geotechnics, Materials, and Construction Processes; MBA in Construction and Property Management), one Erasmus Mundus Master Course (Advanced Masters in Structural Analysis of Monuments and Historical Constructions) and one Doctoral course in Civil Engineering..

The Structural Group is highly involved in the areas of computational modelling of the structural behaviour, experimental testing under displacement control and non-destructive testing. A 400 m^2 structural laboratory equipped with a strong floor has been completed in 2002 and a new laboratory (additional 400 m^2) will be prepared in 2007. Available resources include most of the necessary equipment to perform quasi-static cyclic tests, under deformation control, and state of the art NDT. Research interests includes survey, monitoring, assessment, repair and strengthening of historical structures including non-destructive testing, experimental characterisation of constitutive laws, development and implementation of constitutive laws in the fields of cracking, plasticity and damage mechanics, long term behaviour, and numerical analysis. The group has recently organised a series of conferences, such the 3rd International Seminar on Structural Analysis of Historical Constructions (2001, 500 participants), the Seminar on Masonry Wall Structures (2002, 400 participants), the 4th National Conference on Seismology and Earthquake Engineering (2004, 250 participants), the 3rd International Third International Conference on Bridge Maintenance, Safety and Management (2006, 500 participants) and the 5th International Conference on Structural Analysis of Historical Constructions (2006, 300 participants). Recently funded research projects in the area of masonry / historical structures include Development of Innovative Systems for Reinforced Masonry Walls (European Commission, COOP-CT-2005-18120, 2006-), Development of an Industrialized System for Structural Masonry (Portuguese Innovation Agency, IDEIA-70-00130-2004, 2005-), Reduction of Seismic Vulnerability of Ancient Masonry Buildings, Portuguese Science Foundation POCTI-ECM-61671-2004, 2005-), Efficient Structures: From Materials to Life Performance (Portuguese Science Foundation REEQ/1092/2001, 2004-), Improving the Seismic Resistance of Cultural Heritage Buildings (European Commission, ALA-95-23-2003-077-122, 2004-2006), Industrialized Solutions for Reinforced Masonry Shells (European Commission CRAFT-1999-70420, 2001-2003), and Computational Strategies for the Protection of Historical Churches (Portuguese Science Foundation SAPIENS 33935-99, 2001-2002). The group successfully attracted more than forty sponsored industry contracts in the area of historical buildings, including advanced modelling and non-linear analyses, inspection and diagnosis, as well as strengthening design projects.

The University of Minho will (UMINHO) contribute to the MACH project in fundamental tasks envisaging the establishment of the DST, which will be the basis for the interpretation and evaluation of a monument as a whole (WP9). University of Minho will validate the WSN (WP6) for the structural damage identification by correlating the system with existing standard cabled sensor. Finally, a central contribution for the deduction of the safety levels of a historical building by means of numerical simulation based on advanced constitutive models, with the identification of the damage parameters towards the definition of model of Risk assessment is also foreseen (WP8). This task has direct connections with WP6. UMINHO will participate in the other WPs of transversal (horizontal) character: WP1, 3, 4, 7, and 10.

Research staff:
Prof. Paulo B. Lourenço,
Dr. Daniel V. Oliveira,
Dr. Graça Vasconcelos,
Dr. Francisco Fernandes,
Eng. Luís Ramos.

Prof. Paulo B. Lourenço: Graduation in Civil Eng. (1990), FEUP / University of Porto. Ph.D, Delft University of Technology (1996). Head of Department and Head of the Structural Group. Specialist in masonry, concrete, stone, ancient and historical constructions, structural analysis and testing. Editor of the International Journal of Architectural Heritage. Editorial Board of 5 journals. Scientific Commission of 40+ conferences. Previously involved in several international R&D projects and committees. Currently supervisor of 15 theses and over 400 scientific publications. Over 200 citations in the Science Citation Index.

Dr. Daniel Oliveira: Graduation in Civil Engineering at FEUP / University of Porto (1995). Ph.D, University of Minho (2003. Focus: Strengthening of masonry using FRP, seismology and earthquake engineering.

Dr. Graça Vasconcelos: Graduation in Civil Engineering at FEUP / University of Porto (1996). Ph.D, University of Minho (2005), in "Experimental investigations on the mechanics of stone masonry: Characterization of granites and behaviour of ancient masonry shear walls".

Dr. Francisco Fernandes: Graduation in Civil Eng. (2001), School of Engineering / University of Minho. Ph.D University of Minho (2006)). Focus: old clay brick masonry material, ancient and historical constructions, structural analysis, destructive and non-destructive testing, GPR tomography.

Eng. Luís F. Ramos: Graduation in Civil Eng. (1999), Engineering School / University of Minho. Assistant Researcher, PhD Student (conclusion in July 2007). Focus: damage detection using dynamic identification and sonic testing, monitoring systems.

Recent publications

Lourenço, P.B., Assessment, diagnosis and strengthening of Outeiro Church, Portugal, *Construction and Building Materials*, 19(8), p. 634-645 (2005)

Lourenço, P.B., Luso, E., Almeida, M.G., Defects and moisture problems in buildings from historical city centres: A case study in Portugal, *Building and Environment*, 41(2), p. 223-234 (2006)

Lourenço, P.B., Recommendations for restoration of ancient buildings and the survival of a masonry chimney, *Construction and Building Materials*, 20(4), p. 239-251 (2006)

Feio, A., Lourenço, P.B., Machado, J.S., New and old chestnut wood parallel to the grain: Mechanical behaviour and non-destructive evaluation, *International Journal of Architectural Heritage* (accepted for publication) (Maio, 2006)

Fernandes, F., Lourenço, P.B., On the usage of microdrilling for the assessment of the compressive strength of ancient clay bricks, *Journal of Materials in Civil Engineering*, ASCE (accepted for publication) (Agosto, 2006)

Lourenço, P.B., Feio, A., Machado, J.S., Chestnut wood in compression perpendicular to the grain: Non-destructive correlations for new and old wood, *Construction and Building Materials*, 21 (8), 1617-1627, 2007.

Topczewski, L., Fernandes, F., Cruz, P.J.S., Lourenço, P.B., Practical implications of GPR investigation using 3D data reconstruction and transmission tomography, *Journal of Building Appraisal*, (accepted for publication) (Janeiro, 2007)

Lourenço, P.B., Oliveira, D.V., Seismic Vulnerability Overview of Historical Masonry Churches in Europe, em 1st Canadian Conference on Effective Design of Structures, Hamilton, Canada, p. 453-462 (2005)

Lourenço, P.B., Roque, J.A., Simplified indexes for the seismic vulnerability of ancient masonry buildings, *Construction and Building Materials*, 20(4), p. 200-208 (2006)

Milani, G., Lourenço, P.B., Tralli, A., Homogenised limit analysis of masonry walls. Part I: Failure surfaces, *Computers & Structures*, 84(3-4), p. 166-180 (2006)

Milani, G., Lourenço, P.B., Tralli, A., Homogenised limit analysis of masonry walls. Part II: Structural applications, *Computers & Structures*, 84(3-4), p. 181-195 (2006)

Lourenço, P.B., Pina-Henriques, J.L., Masonry micro-modelling: a continuum approach in compression, *Computers & Structures*, 84(29-30), 1977-1989 (2006)

Lourenço, P.B., Krakowiak, K.J., Fernandes, F.M., Ramos, L.F., Failure analysis of Monastery of Jerónimos, Lisbon: How to learn from sophisticated numerical models?, *Engineering Failure Analysis*, 14(2), 280-300 (2007)

P15 -TT
Transilvania Trust , Romania

The Transylvania Trust is a registered charity, set up by conservation professionals and volunteers in 1996. Our principal aim is to conserve and promote Transylvania's rich and diverse built heritage, to encourage the society to be receptive towards the built environment.

The Trust is active in all fields of conservation: data-recording, inventory, survey, building restoration, maintenance, training, and also scientific research. Among other projects, it has established the Built heritage conservation training centre at Banffy castle, Bontida, in co-operation with the Institute of Historic Building Conservation (UK), as well as organises the only postgraduate course in Historic Building Conservation from Romania, in co-operation with the Babes-Bolyai University, Cluj.

The main objective of the foundation is supporting Transylvanian built heritage conservation and rehabilitation activities. To achieve its main objective, the Foundation participates in actions stimulating the improvement of built environment conservation in general, and the preservation of its heritage values in particular.
The directions and forms of the Foundation's activities are:
- elaborating a regional built heritage conservation strategy for Transylvania, and promoting its bringing into effect;
- contributing to shaping the society's mentality in order for it to understand and support the heritage values of the built environment;
- ensuring a proper background for the training and specialisation in built heritage conservation at all qualification levels, including professional, material and financial support;
- organising conferences, scientific sessions, exchanges of experience, exhibitions, field-trips, workshops, work-camps etc. in the field;
- supporting research, planning and execution activities in the field of build heritage rehabilitation;
- manages and maintains historic buildings and parks, protected areas, natural reserves;
- establishing its own publications, facilitating the flow of information, and putting at the disposal of specialists and the public at large the experience accumulated in the field of built heritage rehabilitation;
- co-operates with domestic and foreign governmental and non-governmental organisations.

The Transylvania Trust was the project leader in 4 European Union supported projects,

- Restoration of the monument – to increase the tourism potential at Banffy castle, Bontida 2001
- Revitalisation of the Banffy castle, Bontida, as a built heritage conservation training centre – supported by the Culture 2000 framework programme – in 2004
- Specialising the workforce from within the building industry in historic building conservation in order to improve its competitiveness supported by the Phare programme – in 2005
- Disseminating know-how at European level and promoting good practice examples - supported by the Culture 2000 framework programme – in 2006

The work of the Transylvania Trust is supported by

1. The European Union
2. Romanian and Hungarian Ministries of Culture
3. Icomos Ro, Hu, US,
4. Europa Nostra
5. ACCR
6. World Monuments Fund

TT will participate in the other WPs of transversal (horizontal) character, that is to say, in WP1, 7, 9 and will specifically contribute to the following activities:

WP2 - Preliminary reflection on the concepts of intervention and knowledge of construction of the Cultural Heritage, as a whole
This approach to understanding a building also defines the approach of the BHCT centre. It is also intensively used in the UK, through the concept of the conservation plan (understanding "significance"). Through the Trust's connections with the IHBC we have access to 1500 conservation professionals from the UK, with extensive experience in this methodology.

WP3 -Diagnosis and intervention techniques. Analysis and repair using compatible materials is the essence of our work. We can offer experience in the implementation of this approach, including analysis of pioneering techniques (e.g. in stone repair, and the repair of vaults at a very specific level, as well as carpentry restoration techniques, and on the effects of the interventions on the whole building at the wider level).

WP 4 - will contribute to the establishment of data format for the Mach Platform and of the monitoring protocols WP6.

WP10 - Diffusion, training and transfer of results. The TT centre has extensive experience in dissemination and transfer of knowledge, at European level, having been involved in 4 European Union projects (2 Phare and 2 Culture 2000 projects as leader organization). In training we have extensive university contacts throughout Europe, and have hosted students from 11 countries (Romania, Hungary, the Czech Republic, Slovakia, Slovenia, Estonia, UK, Belgium, Sweden, France, USA). We would be interested in helping to develop the proposed master's course, but consider that it should also have a practical dimension. Here, the BHCT centre could offer vocational training as part of the course. The project could also benefit from a co-operation with the Postgraduate course on Historic building Conservation, co-organised by the Transylvania Trust and the Babes-Bolyai University of Cluj, Romania.

Research staff:

Prof dr Balint Szabo, the president of the Transylvania Trust, professor of the Architecture and Urban Planning University of Cluj,
David Baxter, European project director Institute of Historic Building Conservation (IHBC, UK),
director of the BHCT centre on behalf of the IHBC
Csilla Hegedus, executive director of the Transylvania Trust, director of the BHCT centre on behalf of the Transylvania Trust

Recent publications

Built Heritage Conservation – techniques taught at the Built Heritage Conservation Training Centre
The Tusnad scientific conference series publications
Scientific articles in the Context (main publication of the IHBC) –
Transylvanian Monument Series – edited until 2003
Construction History Society newsletter August 2007

2.3 Consortium as a whole
Describe how the participants collectively constitute a consortium capable of achieving the project objectives, and how they are suited and are committed to the tasks assigned to them

The MACH consortium has highly specific and interdisciplinary competencies (scientists, conservators) and encloses directly or through subcontracts SMEs both in the repair and maintenance sector and in the development of innovative diagnostic and monitoring stationary and portable instruments.

The main objective of the project is the development of the Decision Supporting Tool (DST) for the diagnosis and the scheduled maintenance of a Monument as a Whole. To its achievement all partners are contributing but the main involvement is attributed to UPC, KUL, TUC, ITAM, TNO and UNROMA1. The DST is an integral part of the MACH platform built mainly by TUC and ICVBC with contributes from all partners. The innovative portable diagnostic tools are developed by the SMEs involved (SINT and INNOWEP) with some contributions from SMARTEC, UPV/EHU, IPPT, BAM and ITAM for the improvement of existing technologies. The innovative Wireless Sensor Network with dedicated sensors will be developed in collaboration with the subcontractor (UNISi) of ICVBC and SINT/HTS and tested in two monumental sites (Ortigia and Porto). The Fiber Optic Sensor (FOS) system will be developed tailored and applied in the common test site (Ortigia) and in two other benchmark sites (Leuven and Gandsk) by the SMARTEC, KUL and IPPT.
The monumental benchmark sites will be described and follow mainly by the respective partners: UMINHO for Cathedral of Porto, KUL for Church of Saint-James – Leuven, IPPT for St. John's church in Gdańsk**,** while the site of Ortigia, managed by UNROMA1 will be used as common test site followed by all partners. The

monumental 3D models will be developed by ICVBC (ISTI), IPPT, UMINHO and KUL. The monitoring procedures of a construction as a whole will be established by all partners; while its application will be follow for structural problems by EPV/EHU, KUL, SINT, SMARTEC, UNROMA1, IPPT, ITAM, BAM and UMINHO, for non structural and environmental parameters by ICVBC, EPV/EHU, TUC, SINT, INNOWEP, IPPT, BAM, and TNO,. The redaction of recommendations and guidelines will be mainly followed by UPV/EHU with the collaboration of all partners. The analytic and numerical models to elaborate expert tools for residual life and residual risk will be elaborated and validated mainly by TUC, KUL, UMINHO, ICVBC (ISTI) while the performance on use and seasonality by ICVBC, ITAM, IPPT, and UPC.
Partner ICVBC will manage and coordinate the project while all partners will participate to the elaboration of an exploitation plan for the diffusion and dissemination of MACH results (leader BAM) such as to participate the meeting and workshop needed for provide a forum for technical discussions, transfer of results and the elaboration of reports.

The research partners are**:**

ICVBC- CNR specialised in scientific studies and monitoring of Cultural Heritage, together with ISTI-CNR specialised in structural analysis and 3D models digitisations and processing, and IA – CNR specialised in acoustis analysis.
- **(**Sub-contractor) *The Department of Information Engineering SPIN Lab – Siena University,* as expert in wireless sensor network.

UPV/EHU, with 3 sectors:
- Faculty of Architecture for structural analysis,
- Plant Biology and Ecology Department for biological decay and control,
- Environmental Analytical Chemistry for chemical diagnosis and processes.

KUL, with 3 sectors and a sub-contract:
- The Raymond Lemaire International Centre for Conservation (RLICC) for analysis, diagnosis and repair of structures of the architectural heritage; the use of three-dimensional techniques of documentation and dissemination in studying built heritage; three-dimensional digital information system for the documentation, representation and conservation of our architectural heritage;
- Civil Engineering department, The Building Materials and Building Technology Division (BWK.MAT), for of the masonry damage diagnostic system and research on environmental damage on mortars;
- Architectural and Urban planning department, Computer aided architectural design lab (ASRO.CAAD), for the use of three-dimensional techniques of documentation and dissemination in the study of the built heritage and on three-dimensional digital information system for the documentation, representation and conservation of our architectural heritage.
- (Sub contractor) *Monumentenwacht Vlaanderen v.z.w.* (MWVl) for collaborate in the survey results in a complete status report of the building, together with indications concerning the needs of works to be carried out in the immediate future or to be planned on medium term

TUC, specialised in Rock Fracture Mechanics: Rock Mechanics, fracture propagation in rocks, dynamic rock fracturing; Experimental Mechanics, Computational Mechanics: Singular integral equations, boundary elements, finite elements; internet based relational databases.
(Sub contractor) *Dept. of Dynamic, Tectonic and Applied Geology Faculty of Geology and Geoenvironment, University of Athens* for elaboration and assemblage of the 3DEC monument model in the platform. Calibration of the models with boundary conditions.

SINT, SINT Technology's expertise are in measurement, testing, analysis and diagnostic services applied to stress, vibration, noise, emissions and the thermodynamic performance of machinery and plants. Production of measuring equipment for special applications, including metal and stone materials, and metal and stone works of art.

(Sub contractor) *HTS* for development of dedicated wirelles sensors

UPC, Expert in the analysis and restoration of structures of architectural heritage and will assess the adequate application of state-of-art concepts, principles and practices oriented the conservation of monuments.

UNROMA1, specialised in the seismic assessment and strengthening of existing buildings,
(Sub contractor) *Provincia Regionale di Siracusa, IX Settore, Pianificazione Territoriale e Protezione Civile*, for collaborating in the management of the common test sites in Ortigia.

UMINHO, highly involved in the areas of computational modelling of the structural behaviour, experimental testing under displacement control and non-destructive testing.

ITAM, specialised in failure analysis of historic materials and structures, damage assessment and monitoring, testing of materials and structures. Expertise in structural diagnostics and strengthening, development of damage mitigation measures, material degradation and compatibility of new conservation /restoration treatments.

IPPT, The principal areas of scientific research conducted by the Institute include theoretical and experimental mechanics of materials, constructions and fluids, computational methods in mechanics, acoustoelectronics and application of ultrasounds for diagnosis of monumental stones.
- (Sub contractor) - Three sub-contractors will work for Benchmark site of St. John's church. *GEOTEST* performs and supplies actual and historical data from geodetic measurements, piezometric surveys and chemical analysis of ground water and will installs a hydraulic network for measurements of presbytery and transept settlements. *CUT* will ensure data of St. John's needed for the construction and verification of a 3D FEM model and for the 3D visualization. Combination of a laser scanning technique, polar survey and digital photographs together with global dynamic characteristics and vibration modes identification will be used. *PUT* work is aimed at building finite element model of Polish benchmark site with implementation of nonlinear material models. The material data obtained from CUT will be used in numerical analyses. The geometry model will be taken directly from the CUT on-site scanning measurements.

BAM, expert in non-destructive damage assessment and environmental measurement methods focuses on determination of measuring parameters, which are relevant for the assessment of structures, damage and contaminations in the natural and built environment.

TNO specialised in the study of decay phenomena of building materials, measures against moisture- and salt-related problems and the effects of atmospheric pollution.
- (Sub contractor) - SNA and Thinkworks have experience in the development and setting up of MDDS and will integrate it into the MACH Platform. Monumentenwacht Nederland will act in a mirror group and make practical experience available.

The SME are

SINT, specialised in laboratory measurement, testing, analysis and diagnostic services applied to stress, vibration, noise, emissions and the thermodynamic performance of machinery and plants
- Production of measuring equipment for special applications, including metal and stone works of art.

INNOWEP, expert in the field of structural, visual, topographical and functional evaluation of materials and surface properties. For these tasks Innowep is developing and producing special measuring instruments.
- (Sub contractor) *Atelier Erich Pummer Gmbh, Wachau,* SME specialized in care and maintenance of Monumental Buildings for daily practice experience in conservation works.

SMARTEC, specialised in measurement and monitoring of civil engineering, geotechnical, oil& gas and automotive structures using advanced sensor systems including fiber optics and GPS. Data management and analysis

The conservation Institution is

TT The society has multidisciplinary character covering all the necessary areas of a restoration processes in the domain of historic building conservation, structural engineer (in field of theory and design), and architects working in the field of design and execution, architecture, archaeology, art history, building engineering, building physics, biology, restoration of mural paintings, stone, glass and wood.

i) Subcontracting:
If any part of the work is to be subcontracted by the participant responsible for it, describe the work involved and explain why a subcontract approach has been chosen for it.

P1 - ICVBC	**Subcontractor**	**Cost**
SC 1	**Department of Information Engineering SPIN Lab – Siena University, Italy**	**70000**
Object	Design, development and production of a Wireless Sensor Networks (WSN)	
Description of the work	The target of the work is the study, the development and the implementation of new hybrid architectures, able to merge and to integrate different kind of sensors and detection systems. This study will not investigate typology and different technologies of structural transducers, but it will take care of to integrate these particular sensors in a WSN. This achievement will be carried out through two main steps: study of physical infrastructure (Hardware), development of procedures and algorithms in order to optimize network resources and reliability of collected data (Software). The following issues will be analysed: o Network topology which better matches the building monitoring needs o Definition of data collection methodology and timing o Hardware power consumption optimization o Integration of structural sensors (transducers) on the single nodes (motes) o Definition of the specifics of the remote control, protocols and interfaces to communicate to access point *Hardware*. First, it is necessary to investigate the WSN architecture which better fulfils the proper monitoring in order to identify the time-dependent global behaviour of a Monument. The study has to investigate how to interface the transducers with the WSN motes, the data reliability, the life time of the devices and the wireless network configurations. Four different typologies of parameters will be monitored: **Mechanical:** strain, stress,deformation and vibration **Ambient:** wind, temperature, humidity and solar irradiance **Precipitation:** rain impact evaluation (experimental) **Pollution:** CO_2, SO_2, NO_2, O_3, CO/NOx monitoring *Software*. It will take care to check the proper network functioning and configuration. The collected data have to be delivered to the central elaboration system, in order to realize the common platform and model, which is the key point of the whole project.	

	WSN have strong power consumption constraint, so it is important to optimize algorithms in order to avoid resource wasting.
Competences	**Alessandro Mecocci** He is full professor at University of Siena. He holds courses in image processing and elaboration, and telecommunication systems. His main interest is on image analysis oriented to hybrid systems and network. His currently research is to combine different technologies to fields of great interest such as healthcare, security and Cultural Heritage monitoring. He is currently investigating emerging technologies related to Wireless Sensor Networks. He held several position both in private companies and public administrations, targeted to the telecommunication development. **Andrea Abrardo** He is associate professor at University of Siena. He holds courses in wireless communications, design of radio-mobile system and numerical transmission. His main interests are in the field of resource allocation strategies for wireless networks, with en emphasis on ad-hoc and sensor networks. He is currently investigating the optimization of radio resource management in WSN location applications. **Alberto Bemporad** He is associate professor at University of Siena. He holds courses in digital control, control system technologies, process and model predictive control, hybrid systems, linear and mixed-integer optimization models, linear system. His main interest are on hybrid systems, model predictive control, optimization, automotive applications, polyhedral computation, robotics. He is currently investigating the application of control system technologies to hybrid system such as WSN. **Daniele Frosali** He is a PhD student and he joined the Department of Information Engineering after two years working in a security information company. His main research is on location algorithms for WSN and its integration with other systems. The goal is to develop WSN technology for different application fields.
References	- A. Bemporad, F. Gentile, A. Mecocci, F. Molendi, and F. Rossi, "A wireless magneto-resistive sensor network for real-time vehicle detection," in Proc. European Wireless Sensor Network Conf., Delft, The Netherlands, 2007. - A. Mecocci, T. Capasso "Generative models for license plate recognition by using a limited number of training samples" IEEE International Conference on Image Processing October 2006, Atlanta (USA) - A. Abrardo, A. Alessio, P. Detti, M. Moretti, "Centralized Radio Resource Allocation for OFDMA Cellular Systems," International conference on Communications June 2007, Glasgow (Scotland) - S. Di Cairano, A. Bemporad, and A. Caldelli, "Moving target detection and tracking in wireless sensor networks," in Proc. European Control Conf., Kos, Greece, 2007. - A. Abrardo, "Non-coherent MLSE Detection of M-DPSK DS-CDMA Wireless Systems with Antenna Arrays," IEEE TRANSACTIONS ON VEHICULAR TECHNOLOGY, June 2003

P3 - KUL	**Subcontractor**	**Cost**
SC 2	**Monumentenwacht Vlaanderen vzw** **Monument Watch Flanders**	**7.600,00 €**

Object	**Supporting Site Surveys on selected case studies**
Description of the work	The target of the work is to: • Enclose the experience of on site systematic inspection system of Monument Watch, within the MACH platform. Therefore, overall input to the MACH platform will be provided by Monument Watch within WP3 (Intervention procedures and more specifically within "Reflection on the concepts of Analysis and Intervention"). Based on experience with preventive conservation and monitoring based preservation strategies a joint strategy will be developed that can be used as a framework for all partners in the project and that will guide the approach of the test case; • Contribute to the construction of the Decision Supporting Tool (DST), WP9, as critical stakeholder. The implementation of the DST will be evaluated for its contribution to preventive conservation and maintenance based conservation strategies using monitoring based on the comprehension of decay / damage processes of a Monument as a Whole. Monument Watch Flanders will serve as end-user partners in the project, from with feedback towards validity and applicability of the MACH-platform towards its use for preventive monitoring in conservation of the built architectural heritage. Therefore, the site surveys are conducted on the selected case study of Ortigia as overall validation experiment.
Competences	Monumentenwacht Vlaanderen vzw (MWVl): is an organisation, founded in 1991, that offers a systematic inspection system focused on regular maintenance to owners of historic (listed) buildings. Monument Watch operates simultaneously on two levels: in short term through immediate action (regular condition surveys - monitoring) on specific buildings it tries to operate a gradual change in mentality in the medium or long term with regards to the conservation of the built cultural heritage. Its central concept boils down to very elementary common sense: the adagio "prevention is better than cure", applied to monuments. To – at present - 4893 member-buildings, based on a voluntary membership, MWVl offers services as an independent advisory body. Monument Watch has a number of carefully recruited, adequately equipped and constantly trained teams (of 2 persons each) at the service of the owner or administrator of the building. Monument Watch not only offers architectural inspections, carried out by 34 specialists but it also has 9 interior specialists. The condition survey results in a complete status report of the building, together with indications concerning the needs of works to be carried out in the immediate future or to be planned on medium term. **Luc Verpoest**, dr. ir. arch. is professor in architectural history and theory of conservation at the department of Architecture, Urban Design and Planning and at the Raymond Lemaire Interntaional Center for Conservation. He is the actual president of Monumentenwacht Vlaanderen v.z.w.. **Anouk Stulens**, is art-historian and Master in Conservation of Historic Towns and Buildings, she is director of Monumentenwacht Vlaanderen.
References	VERPOEST, L. and A.STULENS, *Monumentenwacht, A Monitoring and Maintenance System for the Cultural (Built) Heritage in the Flemish Region (Belgium)*, *Proceedings of the international conference on the occasion of the 30th anniversary of the Raymond Lemaire International Centre for Conservation (1976-2006)*, ed. T.PATRICIO, K.VAN BALEN and K.DE JONGE, Leuven, 2006, pp.191-197. STULENS, A., *Monument Watch in Flanders. An outline*, in *First International Conference Monumentenwacht. Amsterdam – Amersfoort 15 en 16 september 2000*, (Stichting Nationaal Contact Monumenten) (Amsterdam 2002) M.ROSIERS, P.VAN CAYSEELE, W.VAN MEERBEECK, *De financiering van de*

	restauratiebehoefte. (Koning Boudewijnstichting) (Brussel 1998) MONUMENTENWACHT VLAANDEREN VZW, *Schoon schip? Handleiding voor het courant onderhoud van waardevolle kerkinterieurs* (Brussel 2003) responsible editor L.VERPOEST, ed. A.STULENS IDEM, *Onderhoud van ijzerwerk*, (Antwerpen 2006) IDEM, *Onderhoud van metaal in het interieur*, (Antwerpen 2006) IDEM, *Biologische aantasting van hout* (Antwerpen 2005) Etc.

P4 - TUC	**Subcontractor**	**Cost**
SC 3	**University of Athens (UOA), Faculty of Geology & Geoenvironment, Department of Dynamic Tectonic Applied Geology**	**45000**
Object	Elaborate and assemble the 3DEC in the platform. Calibration of the models with boundary conditions.	
Description of the work	The specific work of UOA is to follow all steps required to build a 3D-model based on the in site data-acquisition (on different scales: on micro-, meso- or macro-scale) in order to facilitate the building of the discrete structural model needed in the structural analysis. Validation of the model will be also performed with on site monitoring results. Particular attention will be paid to the heterogeneity of the structure, boundary conditions and appropriate constitutive models in the Model Advisor created by TUC.	
Competences	**Stavropoulou Maria** She is Lecturer at the University of Athens. She has a large expertise in Geotechnical Engineering and in Numerical modelling in Soil and Rock Mechanics. During her PhD she developed a numerical code for the simulation of erosion of low-cohesion rocks due to fluid flow. She has also recently developed a combined Geological-Geostatistical-Numerical methodology for studying the mechanical behaviour of underground excavations in heterogeneous rocks.	
References	Papamichos, E. and Stavropoulou, M (1998). An erosion-mechanical model for sand production rate prediction. Int. J. Rock Mech. & Min. Sci. Vol. 35 (4-5). Stavropoulou, M., Exadaktylos, G.E., Papamichos, E., Larsen, I. and Ringstad, C. (2003). Rayleigh wave propagation in intact and damaged geomaterials. . *Int. J. Rock Mechanics & Mining Sciences* , 40, pp. 377-387. Exadaktylos, G., Papadopoulos, Ch., Stavropoulou, M., Athanassiadou, A. (2003). In lab and in situ assessment of masonry stones mechanical properties through the micro-drilling technique. Structural Studies, Repairs and Maintenance of Heritage Architecture VIII, Edit.C.A.Brebbia, May 2003,173-182. Stavropoulou, M., Giannakopoulos, K. and Exadaktylos, G., (2004). Experimental and numerical study of mechanical cutting of Dionysos marble. In 7th National Congress on Mechanics, June 24-26, 2004, Chania, pp. 236-245. Stavropoulou M.C., Giannakopoulos, K. and Exadaktylos G.E. (2005)., A theoretical and experimental study of rock cutting *J. Mech. Behavior of Materials*. Vol. 16, Nos 1-2, pp. 131-150.	

P5 - SINT	**Subcontractor**	**Cost**

SC4	**H.T.S. s.a.s di Ferrari Marco Alessandro**	**15000**
Object	Development of sensor interfaces for the Wireless Sensor Network. On field assistance to the installation and checking of the sensors	
Description of the work	Development of sensor interfaces for the Wireless Sensor Network relevant to the crack sensors and strain gauge sensors On field assistance to the installation and checking of the sensors in the sites of Florence Baptistery, Ortigia and Porto	
Competences	**Marco Ferrari - HTS** H.T.S designs and develops electronic systems for the industrial automation and special measurement systems, using microprocessors, industrial PC or PLC. The company has experience in: - measurement of temperature, relative humidity, and vibrations, and other quantities - software development (LabView) - software and hardware for microprocessors - wireless applications. Particular engagement has been dedicated in the development of special measurement systems for the monitoring of phenomena that act on the degradation of the architectonic structures in particular in Cultural Heritage field.	
References	.	

P7 - INNOWEP	**Subcontractor**	**Cost**
SC 5	**Atelier Pummer, Rossatz, Wachau, Austria**	**10.000**
Object	**Supporting for the on site practices**	
Description of the work	Contribute to the state of the art for diagnostic practical applications and in the final Decision Supporting Tool (DST), WP9, as critical stakeholder. The implementation of the DST will be evaluated in relation with dayly practical conservation intervention on monumental heritages. Atelier Pummer will serve as end-user partners in the project, from with feedback towards validity and applicability of the MACH-platform towards its use. Moreover will contribute to the exploitation and diffusion of the outcomes of the project.	
Competences	One of leading companies in Austria for the application of new technologies for care and maintenance of mounumental buildings	
References	One of leading partners in HOSTOCLEAN project, Publication in Lacona6:	

P9 – UNROMA1	**Subcontractor**	**Cost**

SC 6	**Provincia Regionale di Siracusa, IX Settore, Pianificazione Territoriale e Protezione Civile**	**10000**
Object	Support in coordination and management of the common test site in Ortigia	
Description of the work	The Provincia Regionale di Siracusa is the owner of many historical buildings in the historical center of Ortigia. One of these is the former Borbonic Jail located in the Graziella quarter, which constitute the objectives of the joiny study of the partnership within the MACH project. The Provincia Regionale di Siracusa will ensure its presence in all foressen meetings (in Italy and abroad) and all field applications, where they will set the optimal conditions for carrying out the on site testings: preparing access to the sites, geometrical survey of the buildings, workmanship for practical execution problems related to device installation, reservation of hotels, ecc.	
Competences	**Angelo Di Pace** Engineer, he is the Manager of the Office of Territorial Planning and Civil Protection of the Provincia Regionale di Siracusa.	
References	Scalora, G., Riggio, A., Di Pace, A., Miraglia, C. (2007). Pianificazione territoriale e protezione civile. *X Italian Conf. ESRI.* Roma, 18-19 April.	

P11 - IPPT	Subcontractor	Cost
SC 7	**Cracow University of Technology CUT (Environmental Engineering Faculty EEF-CUT, Institute of Structural Mechanics ISM-CUT) – Cracow, Poland**	**48000**
Object	On site structural diagnostic. On site mechanical parameters determination.	
Description of the work	The work offered by the CUT will be carried out on the Benchmark monument (*St. John's Church in Gdańsk - north Poland)*. The target of the work is to obtain data of the Benchmark monument needed for the construction and verification of a 3D FEM model and for the 3D visualization. The work consists of two parts: *1) Identification of the Benchmark morphology by use of the combination of a scanning technique, polar survey and digital photographs* This is an effective method of a precise inventory survey of historical structures. The scanning will be taken by auto-tracking total station. The idea of the proposed method is to differentiate the scanning grid, for example a main block may be scanned by grid of 1m×1m, but details by 10cm×10cm or even 5mm×5mm. Orientation points and important details of object shape are measured by spatial polar method. A standard camera is used to provide digital photographs necessary for wall surfaces rendering as well as localization of cracks. The 3D model is produced by special software. The model meets high structural and architectonic demands of inventory accuracy. *2) Identification of global dynamic characteristics and vibration modes of the Benchmark* Structural response of the Benchmark monument will be tested. On site dynamic characteristic of the masonry structure will be identified under influence of mechanical dynamic loads caused by wind and town traffic. Vibrations will be measured in selected points of the Benchmark monument using high sensitivity accelerometers of PCB and 16-chanell acquisition systems ESSAM Traveller Plus and TEAC. Outputs will be analysed in Mathlab system using modal identification techniques to obtain the modal parameters:	

	resonant frequencies, mode shapes, damping coefficients and vibration ground transmission functions. The data will be used as input and verification data for the identification procedure for finite elements modelling.
Competences	**Bogdan Wolski** He is an associate professor at Cracow University of Technology and the head of the Engineering Surveying Section at the Environmental Engineering Faculty. He holds courses on engineering surveying. His main research interest is focused on optimization of different technics of measurements for the purpose of inventory as well as monitoring of deformations and displacements of structures. His currently research is to optimize a laser scanning measurement technology for different types of structures having in mind data reliability and accuracy problems to produce 3D model useful for structural analysis. **Krzysztof Stypuła** He is associate professor at Cracow University of Technology. He holds courses in structural statics and dynamics, design of buildings in seismic areas and dynamic measurements of buildings. His main interests are in the field of measurements and calculations of seismic and ambient vibrations of buildings, evaluation of dynamic response of buildings and evaluation of influence of ambient vibrations (especially transport vibrations) on people in buildings. He is expert in investigations (experimental measurements, monitoring, simulation and protection) of building vibrations caused by transport especially by train passages in metro tunnels. It concerns also historical buildings. He designed system of monitoring of vibrations in Warsaw metro and vibroinsulation system in construction of railway track in Warsaw metro and railway tunnel in Warsaw. He is currently preparing a prognosis (numerical simulation by means of FEM) of dynamic influences on existing buildings and people in buildings at the new section of Warsaw metro with proposal of protection of these buildings. He designed a protection against vibrations in the structure of several new buildings near the metro lines and railway lines. **Arkadiusz Kwiecień** He is assistant professor at Cracow University of Technology. He holds courses in structural statics and dynamics, design of buildings in seismic areas and dynamic measurements of buildings. His main interests are in the field of measurements of vibrations and deformations of buildings (including monitoring) as well as in static and dynamic diagnosis of historical structures. He works currently on innovative repair and protection methods dedicated to heritage monuments, particularly cracked masonry structures localized in areas of dynamic influences. **Cezary Toś** As an assistant professor in Engineering Surveying Section at Environmental Engineering Faculty of CUT he delivers lectures on measurement survey technics. As an survey expert he is experienced at practical application of different technics of geodetic measurements. His research activity is focused on integration of different technics. At present he deals with combinig a laser scanning, digital images and classical geodetic methods of measurement. *In the frame of the ISM-CUT there is Laboratory for Research of Deformations and Vibrations of Structures with competent staff.*
References	• Kwiecień A., Zając B., Ciurej H., Pęcherski R.: *Application of flexible joints in dynamically excited structure of damaged buildings.* 6th International Conference of EASD EURODYN'2005, Paris 2005. • Kawecki J., Stypuła K.: *Measurement and interpretation methods of evaluation of bell motion influence on a historical tower construction and people inside*, (in polish). VII

	Conf. Scientific-Technical REW-INŻ'2006, Kraków 2006. • Kwiecień A., Zając B., Stecz P., Kubica J.: *Flexible Joint Method (FJM) – a new approach to protection and repair of cracked masonry.* 1st European Conference on Earthquake Engineering and Seismology (1st ECEES), Geneva 2006. • Kwiecień A. Zając B., Kubica J.: *Repair of cracked historical masonry structures by use of the Flexible Joint Method (FJM) – laboratory tests*. 5th International Conference on Structural Analysis of Historical Constructions, New Delhi 2006. • Toś C., Wolski B., Zielina L.: *Inventory surveys of historical structures by scanning tacheometry*. Proc. of the 8th Bilateral Geodetic Meeting Poland-Italy. Reports on Geodesy No.2 (77) 2006	
SC8	**Technical Implementations Enterprise GEOTEST, Gdansk, Poland**	**9000**
Object	Installation of measurement systems in St. John's church in Gdańsk Delivering of data about the church	
Description of the work	1. Installs a hydraulic network for measurements of presbytery and transept settlement (labour and materials). 2. Helps SMARTEC in installation of settlement and slits gapes optical fibre sensors. 3. Delivers data from historical geodetic measurements, piezometric surveys and chemical analysis of ground water.	
Competences	**Edward Szczepański** geologist, specialist in engineering geology **Magdalena Radzewicz -** engineer **Adela Szczepańska** student of AGH University of Science and Technology in Cracow, Faculty of Geology, Geophysics and Enviromental Protection	
SC 9	**Poznan University of Technology PUT (Faculty of Civil and Environmental Engineering, Institute of structural engineering, Department of Computer Aided Design), Poznan, Poland**	**27000**
Object	FE modeling and numerical determination of mechanical property.	
Description of the work	The main goal of PUT work is aimed at building finite element models with implementation of nonlinear material models. The material data obtained from CUT part of work will be used in further numerical analyses. Moreover, the geometry model will be taken directly from the on-site scanning measurements. The crucial work contains three parts: *1) Building of 3D geometry model with topology optimization* The data will be used exclusively to build the 3D model which will be based only on the on site measurements. The scanned grid serves as an input to obtain the computer model (including architectural details) at the different precision level. The real cracks and masonry failure will be taken into account. *2) Implementation of accepted material models* The material model, proposed by IPPT and UMINHO, will be subjected to numerical analyses. The reliability of FE results need to rely on a wide-array great approach which takes into consideration geometry, material and method of load distribution as well.	

	3) FE Results finding The main target of this part of work is the comparison of the numerical results with the experimental calculations. All of experimental tests will be recalculated and analyzed with numerical approach. The projected outcome will incorporate the solution of static stresses and dynamic response of analyzed structure.
Competences	**Tomasz Łodygowski** He is professor of civil engineering, in particular computational mechanics, at the Department of Civil and Environmental Engineering of Poznan University of Technology. The thirty years experience is in the fields of the analysis of structures and materials under static and dynamic loadings including fast impacts and blasts. The interests are focused on concrete and masonry structures and the failure and fracture criteria which can serve in the estimation of limit loads of the structures. He has a great experience in analyses of plastic behavior and the localization of strains in structures. He is the head of the Division of Computed Aided Design at his home institute which collects the staff of 10 people. **Piotr Sielicki** He is Ph.D. student at the Department of Computer Aided Design in PUT. He has experience in practical use of numerical codes and numerical geometry topology processing. His research is mainly focused on the failure of masonry elements under the dynamic loads and stress distribution in vaults. He is currently investigating the application method to estimate the pressure distribution on the brick wall which is subjected to explosion.
References	- P.B. LOURENÇO, "Computational strategies for masonry structures" Delft University Press, 1996. - P. Rapp, P.W. Sielicki, "Case Study of Masonry Pillars Reinforcement in a Medieval Church" Structural Analysis of Historical Constructions 2006, New Delhi, 2006. - L.F. Ramos, P.B. Lourenco, "Modeling and vulnerability of historical city centers in seismic areas: a case study in Lisbon", Engineering Structures, 26, 1295-1310, 2004. - J. Jasieńko, T. Łodygowski, P. Rapp, „Naprawa i wzmacnianie wybranych, zabytkowych konstrukcji ceglanych", Poland, 2006

P13 - TNO	**Subcontractor**	**Cost**
SC 10	**Silvia Naldini Advice (SNA)**	**25000 €**
Object	**Structuring of new knowledge in expert system MDDS**	
Description of the work	The main role played by SNA is to help developing the MDDS system in a targeted way, to make it an effective work instrument inside the MACH Platform. SNA, in collaboration with TNO and ThinkWorks, will structure and insert the new knowledge acquired in the MACH project into the DST system. This will result in a new version of the MDDS system having an enhanced functionality, in which monitoring of the damage development in time and evaluation of the risk of damage will be taken into account.	
Competences	**Silvia Naldini**, art historian, has been active for longer than 15 years in the field of the conservation of monuments. She has worked for TNO in many EU projects. In 2000 she started an enterprise, called SNA, also co-operating with TNO. She has worked in national and international projects on the study and diagnosis of damage to monuments, especially contributing in the field of restoration philosophy and	

	taking part in the development of expert systems. S. Naldini is specialised in selecting and structuring relevant knowledge, acting as an intermediate between the software experts, the scientists and the users. Has experience in the development of effective, easily accessible and targeted damage overviews (damage atlas).	
References	Franke, I. Schumann, R.P.J. van Hees, L.J.A.R. van der Klugt, S. Naldini, L. Binda, G. Baronio, K. Van Balen, J. Mateus, *Damage Atlas. Classification of Damage Patterns found in Brick Masonry*, Research Report No 8 Vol. 2, European Commission, 1998, Fraunhofer IRB Verlag, ISBN 3-8167-4702-7. Balen, K. van, J. Mateus, L. Binda, G. Baronio, R. van Hees, S. Naldini, L. van der Klugt, L. Franke, *Expert system for the evaluation of the deterioration of ancient brick structures*, Research Report no 8 (vol. 1), European Commission, 1999, ISBN 92-828-6448-0, 1999. Naldini, S., R.P.J. van Hees, M. Pilar de Luxan, F Dorrego, K.E.P. Van Balen, R. Hayen, L. Binda, G. Baronio, *Historical pointing and the preservation of its value*, in 'Structural Studies, Repairs and Maintenance of Historic Buildings VII', WIT-Press Southampton, Boston 2001, pp. 671-680. Naldini, S., R.P.J. van Hees, B. Lubelli, F. Zezza, F. Auger, *Implementing an expert system in the study of sea salt damage*, 6th Int. Symp. On the Conservation of Monuments in the Mediterranean Basin, submitted Sept. 2003.	
SC 11	**ThinkWorks**	**15000 €**
Object	Adaptations in the underlying software of MDDS into the MaP in order to fine tune the reporting to the specific needs of MACH	
Description of the work	Thinkworks will make adaptations to the software of the MDDS system, more specifically related with new module DST for monitoring of the damage development.	
Competences	ThinkWorks has a long experience in the development of decision support systems. ThinkWorks has collaborated with TNO in the development of several expert systems (e.g. on biological growth, moisture problems, concrete structures) ThinkWorks software IO (Intelligent Objects) forms the tool in which MDDS has been developed.	
References	www.thinkworks.nl Ralph Vanhauten [r.vanhauten@thinkworks.nl]	
SC 12	**Monumentenwacht**	**5000 €**
Object	Feedback to the development of survey and sampling procedure.	
Description of the work	Monument Watch will give feedback to the development of survey and sampling procedures. Monument Watch, thanks to its everyday experience, will be able to give a sound evaluation of the applicability of the survey, sampling and monitoring procedures on a large scale.	
Competences	Monument Watch (the organization Monumentenwacht Nederland) was founded in 1973, with the aim of preventing decay of the Dutch cultural heritage by timely observation of maintenance deficiencies. Its philosophy has subsequently been adopted by organizations in a number of countries in Europe. Its main tasks are the periodic inspection of monuments, reporting on the conditions of buildings and advising of the owner on short and long term maintenance policies. About 15000 inspections are carried out each year. As a result, Monument Watch has extensive experience with the evaluation of damage in	

	monuments.
References	Monumentenwacht has been active in several EU projects: COMPASS, Saltcontrol

2.4 Resources to be committed

The whole cost proposed by the partnership reachs about **4.3 ME**, without any external receipts. The total of resources engaged in the project is **347.5 man/months** for a foreseen duration of **4 years**. Naturally some partners, having pluridisciplinary competences, are involved in more that one research activity and with higher effort in personnel dedicated to the work. The requested EC contribution of about **3.25 ME** is considered enough to achieve the objectives proposed, taking into consideration the duration, the complexity and the real innovation introduced, by the proposal, in the field of Monumental Heritage Conservation. Nevertheless, the European dimension of the problems to be fronted, the required integration and establishment of common guidelines require the participation of partners coming from different countries with different specializations.
The following major costs (sub-contracts, travels, durables and consumables) have been scheduled by different partners for the achievement of the objectives proposed.
The specification of the sub-contracts are reported at point 2.3 i (pag 112). The needs for the stipulation of the most relevant are:
- ICVBC involves in the project specific competences in the field of developing sensorial networks, knw-how of the UNISi. The WSN should become a very innovative low cost monitoring system. UNISi is collaborating with ICVBC in a regional (Tuscany) network composed by several research institutions and universities addressed to the scientific methodologies applied for the study and the conservation of the CH.
- TUC involves in the project specific competence (TUA) in the elaboration of numerical codes for studying mechanical behaviours and to discretize 3D models.
- IPPT involves in the project the competences required for built the 3D model (CUT) and to install and execute the geological (GEOTST) tests for the foundation at the benchmark site.
- TNO involves in the project specific competence for the structuring (SNA) and modifing (Thinkworks) the MDSS software in order to be merged into the MaP.

The travels expenses are quite balanced and necessary for participating both to the project workshops and to the on site monitoring campaigns at the common benchmark monumental site of Ortigia. The latter will be specifically addressed by partners ICVBC, UPV/EHU (with 3 units), SINT, INNOWEP, BAM, TNO, ITAM, IPPT, UNROMA1.

A detailed description of these costs are reported in the following tables:

Partner	Sub contract	Durables	Consumables	Travels
CNR - ICVBC	70000		25000	30000
UPV_EHU			32000	35000
KUL	7600	8500	38125	26000
TUC	45000	20000	5000	22100
SINT	15000		35000	29000
SMARTEC		47000	38000	12000
INNOWEP	10000	9000	25000	21000
UPC				21000
UNROMA1	10000			20000
ITAM			27000	21720
IPPT	84000	49000	9500	25000
BAM			25000	27000
TNO	45000		1500	20000
UMINHO		17500	18000	25000
TT				16000
total	**276600**	**151000**	**279125**	**335820**

DURABLES

Participant n°	COST	Type	Use in the project
3 - KUL	**8500**	- 1server for 3D-scanning data - 2 PC	Realization of the 3D model
4 - TUC	**20000**	- 1 server for installation of web-driven Mach Platform - 1 portable microdrilling tool - 1 portable indentor	- Installation of Mach's Platform (WP4) - Performance of in situ non destructive measurements for mechanical properties and damage assessment of rocks (WP5)-
6- SMARTEC	**47000**	Fiber oprics, Reading units and junction boxes for 3 FOS	Realization of the FOS system (3)
7 - INNOWEP	**3500** **3500** **2000**	Camera chip evaluation board Circuit board development kit Luxmeter	Improvement of the Surface Meter
14 - UMINHO	**7500**	Data acquisition board and PC	Elaboration of the 3D model

CONSUMABLES

Participant n°	COST	Type
1 - ICVBC	**30000**	Motes and dedicated environmental sensors for 2 WSN
2 – UPV/EHU	**32000**	Build and tests on stones and brick masonry samples Works on 500 strain gages + 20 steel bars Chemicals, gases and lab ware to perform the diagnostic analysis (chemical and biological) and to develop the new NDT/MDT
3 - KUL	**5000** **7500** **7000** **3000** **4000** **8000**	Rental Laser scannerHDS3000 for 5 days Rental Laser scannerHDS4500 for 5 days Educational Licence Rapidform Educational Licence Cyclone License Matlab License FEM
5 - SINT	**33000**	Electronical and mechanical components for the portable system, microcores and drillbits, Strain gauge rosettes and accessories, vibrating wire strain gauges, other sensors and electronic interfaces for long term monitoring,

6- SMARTEC	**38000**	Sensors and software for 3 FOS
7 - INNOWEP	**9000** **4000** **4000** **1500** **6500**	Lens and collimator design License costs for USB Implementers Forum Inc. To get VIDs/PIDs camera chips small series Graphic layout editor for printed circuit boards Spare parts
10- ITAM	**15 000** **3 000**	Vibration monitoring system including motes and sensors, low vibration seismometers Moisture content gauges (soil and masonry)
11 - IPPT	**3500** **5000**	Diamond core drill bits Diana software Licence
12- BAM	**25000**	- Electronic components for active thermography (heating systems, automatic scanner unit) - Set-up of test specimens (material) - Chemical components for element analysis
14- UMINHO	**9000** **10000** **9000**	- Electronical components for the wireless system and vibrating strain gauges - MEM sensors - Diana software licence

3. Impact

3.1 Expected impacts listed in the work programme

Describe how your project will contribute towards the expected impacts listed in the work programme in relation to the topic or topics in question. Mention the steps that will be needed to bring about these impacts. Explain why this contribution requires a European (rather than a national or local) approach. Indicate how account is taken of other national or international research activities. Mention any assumptions and external factors that may determine whether the impacts will be achieved.

Expected impact:

More cost-effective preventive conservation and maintenance, applicable to a wide variety of cultural assets and to different environmental conditions. The developed methodologies should be broadly accepted and used beyond the EU.

Expected impact in this call	**Contribution of MACH and planned steps**	**Assumptions and external factors that may determine whether the impacts will be achieved**
More cost-effective preventive conservation and maintenance	New tools for cost efficient and effective monitoring and assessment: - Development of low costs Stationary Wireless Sensors (SWS) and Fiber Optic Sensors (FOS) - Development of portable non-destructive (NDT) and minor destructive (MDT) technologies for damage assessment (e. g. HD, Surface meter) Considerations of **Charter of Krakow 2000** (Includes principles for conservation and restoration of built heritage and the planning of restoration projects according to appropriate technical and	Towards the end and several years after the project, the new tools will be used by several end-users, feed-back in the decision supporting tool is used by the end-users

	structural criteria) Consideration of **Declaration of London 2004** (to protect and safeguard European Cultural heritage through scientific and technological research to promote favorable educational, training and knowledge transfer programs) Consideration of **Message of Prague conference 2006** (protection of the sustainability of European cultural heritage require innovative approaches and technologies, advanced integrated modelling and optimised use of the research infrastructure)	
Applicability to a variety of cultural assets	DST is an expert system that can be applied to a great variety of "whole" monumental heritage irrespective of its nature" : churchs, palaces, castles, bridges, towers, etc. Once the monument is documented and 3D digitalized, and specific damage data (structural and/or material) are monitored it will be able to suggest indicative possible solution related to risk assessment and scheduled maintenance programmes.	The case studies will be the first input and stored in the Data Base of the MaP. This is open and will be implemented with new cases either from partners and end-users.
Applicable to different environmental conditions	The analytical and numerical simulations tools have been developed considering different environmental conditions like: - earth quake - traffic vibrations - re-use, uploading - flood, moisture, humidity - climate - chemical damages - air pollution - biodeterioration	Application of DST at historic building structures in different geographical locations and climatic conditions:
Broadly acceptance and use of the developed methodologies beyond the EU	Development of guidelines and recommendations Contact to national and international organisations like ICOMOS, RILEM (e. g. TC SAM), CEN CT346, UNESCO, Professional organisation involved in the care and maintenance of monuments at European level.	National and international agreement for the use of the DST.

Requirement of a European approach

The described objectives and measures require deep knowledge and a wide experience because as European Culture exhibits a large variety, the same statement can be made about European architectures. A part of stilistic differences and the great variety of construction material used all around Europe, aslo climatic influence must be considered: in northern regions suffer mostly from moisture and freeze-thaw cycles, in southern countries thermal load and seismic risks have to be considered as major threats for valuable monuments. Another important issue is the different attitude of the inhabitants and authorities towards their Cultural Heritage. Although partly large efforts were attempted to maintain and protect historic buildings, there is a lack of higher-ranking strategies how to channel these initiatives in such direction.

Therefore, the expected impact concerning : an optimum selection of tools for monitoring and non-destructive and minor destructive assessment; a cost efficient and effective application; a consideration of a variety of cultural assets and of different environmental conditions; can only be achieved by cross-national European co-operation. With the selected consortium involving 10 different European countries this aspect will be realised taking into account the following horizonts:

Horizon 2010	**Assessment, Monitoring & Diagnosis**
Breakthrough	**Innovation required**
Objective, quantitative and minor destructive methods and technologies for sustainable monitoring and diagnosis of Cultural Heritage structures	Development of new and existing non-destrucitive and minor destructive monitoring and diagnosis methods and multichanel monitoring systems. (**Link to WG5)**
Enhacement of reliablity of monitoring and diagnosis methods and technologies	Validation of monitoring and diagnosis systems related to the testing problems, classification of testing problems, advanced signal processing for user friendly visualisation of results (**Link to WG6)**
Guidelines for monitoring and diagnosis methods	Development of guidelines for the on-site performance of measurements (technical guidelines and expert programs) (**Link to WG7)**
Integral knowledge about behaviour of structure	Modelling of structures and categorization of results. (**Link to WG8)**
Horizon 2020	
Intelligent monitoring systems	Enhancement of resistance against enviromental influences and reduction of required maintenance of installed monitoring sytsems
Regular application of monitoring and diagnosis systems for assessment of old and quality assurance of repaired/new structures	Optimisation of monitoring and diagnosis methods, adaption to new materials **(Link to WG 5 and WG 6)**
Guidelines for the application of monitoring and diagnosis methods in regual assessment	Development of guidelines with the contribution of equipment designers, service providers and end users (**Link to WG7)**
Education and training courses on the application of monitoring and diagnosis methods	Development of education and training manuals, test specimen and selection of on-site buildings (**Link to WG10)**
Horizon 2030	
Integral structural assessment	Development of programs to carry out a integral structural assessment starting of the diagnosis, monitoring and structural calculations results. (**Link to WG8)**
Integration of building assessement, monitoring and diagnosis in management systems	Development and implementation of advanced management systems for historic buildings (**Link to WG 9**)
Enhancement of quaility in the cities by accessible cultural heritages which are assessed periodically regarding saftey and durability	Development of reliable methodologies for efficient combination of monitoring and diagnosis systems (**Link to WG 9**)

Consideration of other national and international research activities

MACH will strongly interact with previous and current projects (see ANNEX1). Furthermore, synergies with education institutions are foreseen being several Technical University participating as partners (TUC, UMINHO, UPC UPV, UNROMA1) and doctoral students, engineers and architects will be trained in seminars and workshops in which the outcomes of the project will be diffuse. The results will be exploited in high quality scientific journals and in sectorial or more general International Conference such as SPRECOMACH (June 2008).

Approval letters to the proposal (See ANNEX 3) have been received from :

- *Provincia Regionale di Siracusa, Italy*

- Soprintendenza Regionale della Calabria, Italy
- Opera del Duomo, Firenze,Italy
- Associazione delle Dimore Storiche Italiane, Sez. Toscana, Italy
- ETCP - Piattaforma Tecnologica Italiana delle Costruzioni – Area Patrimonio Culturale, Ancona Italy
- Monumentwatch FL, Anversa, Belgium
- Generalitat de Catalunya- Department de Cultura, Direcció General del Patrimoni Cultural, Barcelona, Spain
- Direccion Generales de Bellas Artes y Bienes Culturales, Direccion Patrimonio Historico, Madrid, Spain
- Asociación Española de Normalización y cerificatión – AENOR, Madrid, Spain

3.2 Dissemination and/or exploitation of project results, and management of intellectual property

Describe the measures you propose for the dissemination and/or exploitation of project results, and the management of knowledge, of intellectual property.
(Maximum length for the whole of Section 3 – ten pages)

These activities have been inserted into a specific working package of the project **WP10**

Workpackage number	**10**	**Start date or starting event:**			**T1**		
Workpackage title	**Dissemination and Exploitation**						
Activity type[1]	**RTD**						
Participant n°	**ICVBC**	**UPV/EHU**	**KUL**	**TUC**	**SINT**	**SMARTEC**	**INNOWEP**	**UPC**
Person-months per participant	**0.5**	**3**	**1**	**0.5**	**1**	**1**	**1**	**0.5**
Participant n°	**UNROMA1**	**ITAM**	**IPPT**	**BAM**	**TNO**	**UMIHO**	**TT**	**Total**
Person-months per participant	**0.5**	**1**	**1.5**	**3**	**1**	**0.5**	**3**	**19**

Objectives

- Dissemination of the project results and deliverables through training, seminars, workshops and dedicated conferences.
- Exploitation of the innovative results of the project, diffusion and transfer of the results to companies (especially to SME) and end-users.

Description of work

Task 10.1 Dissemination of the project results and gained knowledge:

The co-operation with the end-users is one of the most important features of the project. This target group consists of restorers, architects, researchers, engineers, owners of monuments, politicians, decision makers and many others (see ANNEX 3). It is important to find a common language, which is suitable to address these different groups. Further on, the end users (which are not direct partners of MACH) have to be integrated into the project very early through workshops and seminars and by inviting them to participate in a **MACH mirror-group**. The planning of dissemination activities will be carried out during the project meetings by coordinator, WP-Leaders and MACH mirror-group

members. The following activities are planned:

- Set-up of a Web Site with internal part (only accessible for the partners) and an external part (for the end users) (ICVBC)
- Mach-Platform, which will be made accessible to possible end-users (public and private) in the field of conservation of the European Monumental Heritage (TUC)
- Quality Control of deliverables, which will be issued in the form of guidelines and/or recommendations and reports. Harmonisation of language and approach
- Publications at Conferences and Seminars and at scientific and popular journals (all)
- Consideration of sociological aspects: integration of environment and public (all)
- Organisation of seminars including a workshop with presentations from partners and external invited speakers like owners and managers of Cultural Heritage, European and International associations and networks related to Cultural Heritage (UNESCO, ICOMOS, ICOM, RILEM, Monumentenwacht) and co-ordinators of other related projects (NOAH's ARK, Salt Control and Compass, ONSITEFORMASONRY, CHEF, ViHAP3D, EPOCH, CULT STRAT, DIAS etc.) at an early stage of the project (UPC, SINT, UPV/EHU, BAM, …)
- Organisation of a seminar including a workshop after project duration of three years for presenting the achieved results and for optimising the remaining work plan of the project (UPC, SINT, …)
- Training course at the end of the project for introducing the mirror group and interested end-users into the MACH Platform
- Lessons and training courses at the universities (UPV/EHU, KUL, TUC, UPC, UMINHO)

Task 10.2 Exploitation of innovative results of the project

Exploitable results of MACH will be the innovative results like new methods and technologies, the MACH Platform with the integrated Decision Supporting Tool and further databases and models of different materials (including geomaterials) predicting vulnerability and durability.

New methods and Technologies (innovations)
The new methods for diagnosis/monitoring have the potential to be developed into commercial products, which can be established at the market by companies and especially by SMEs. The project can only support these activities until an early prototype level. The following methods and technologies will be considered among others:

- New NDT methodologies to in-situ extract the inorganic and organic compounds trapped on the surface of stones and mortars (UPV/EHU)
- Software tool for time and frequency related analysis of thermal data recorded with active thermography (BAM)
- Portable device for NDT/MDT, for on site stress analysis and material characterization, comprising a software for the prediction of the material properties (UCS, UTS and E) and for the stress calculation (SINT, INNOWEP, IPPT).
- Wireless Sensor Network with MEMS for the condition monitoring of a monument (WSN) (ICVBC/UniSi, SINT/HTS).
- It is expected that Polish spin-off SME will be established to exploit the innovative technology of micro-core testing (CoDiT method) as MDT diagnostic tool in combination with other MACH innovative tools.

The **exploitation plan** will include:
Market study: The market for diagnosis/monitoring devices will be analysed to identify potentials and

barriers for further opening of the market and developing strategies for implementation of new products.
Patents: UPV/EHU Partner will proceed to protect by patent applications the successful New NDT methodologies to in-situ extract the inorganic and organic compounds trapped on the surface of stones and mortars because there is nothing in the market based in the proposed alternatives.
Definition of Products: Based on the market study and the development of the WPs, products will be defined and specifications for exploitation and promotion of these products will be set-up. The added value of each product will be assessed.
Promotion of Project results: At an early stage, potential users will be addressed by promotion of the project results in the EU. Focus will also be set on New Member States and Mediterranean countries.

MACH Platform with the integrated Decision Supporting Tool, implementation in knowledge based decision tool
The knowledge gained in the project will be used to implement background information in the MDDS system. In this way knowledge transfer is reached among the group of users of MDDS (including several MSc University courses). The system will be able to address the user suggesting the most suitable (low intrusive) investigation techniques and methods adapted for each specific situation.

Consortium Agreement
For internal management of knowledge and of intellectual property, at the beginning of the project, a Consortium Agreement will be signed by all partners, minimising the possibility of internal disputes about patent rights, pre-existing knowledge and others.

European Construction Technological Platform (ECTP)
The topics proposed by UPV/EHU (Fac. of Architecture) are included in the Strategic Research Agenda (SRA) of the European Construction Technological Platform (ECTP). Santiago Sánchez-Beitia is the coordinator of the Horizontal Issue 2 "Standards and Specifications" of the Cultural Heritage Focus Area of the ECTP.

SPRECOMAH project (www.sprecomah.eu)
Different partners are involved in this activity and this will help tailoring the activities for a maximum impact and dissemination of the MACH project during the 2nd Seminar (paris 2June 2008).

Task 10.3 Training activities

EPV/EHU is proposing, at the end of the peoject to include in the framework of MACH a Europen academic master within the umbrella of the technical universities participating. The Basque University has a postgraduate Programme of Excellence called "Environmental pollution and resources" where a Master in topics related to MACH can be enclosed.

Deliverables

D10.E – Exploitation and dissemination plan (first version at M12, updated every 12 months)
D10.SW.1 – Seminar with workshop at M25
D10.SW.2 – Seminar with workshop at M41
D10.T – Training course at M46
D10.5W– Web-site at M4

4. Ethical Issues

	YES	PAGE
Informed Consent		
• Does the proposal involve children?		
• Does the proposal involve patients or persons not able to give consent?		
• Does the proposal involve adult healthy volunteers?		
• Does the proposal involve Human Genetic Material?		
• Does the proposal involve Human biological samples?		
• Does the proposal involve Human data collection?		
Research on Human embryo/foetus		
• Does the proposal involve Human Embryos?		
• Does the proposal involve Human Foetal Tissue / Cells?		
• Does the proposal involve Human Embryonic Stem Cells?		
Privacy		
• Does the proposal involve processing of genetic information or personal data (eg. health, sexual lifestyle, ethnicity, political opinion, religious or philosophical conviction)		
• Does the proposal involve tracking the location or observation of people?		
Research on Animals		
• Does the proposal involve research on animals?		
• Are those animals transgenic small laboratory animals?		
• Are those animals transgenic farm animals?		
• Are those animals cloning farm animals?		
• Are those animals non-human primates?		
Research Involving Developing Countries		
• Use of local resources (genetic, animal, plant etc)		
• Benefit to local community (capacity building ie access to healthcare, education etc)		
Dual Use		
• Research having potential military / terrorist application		
I CONFIRM THAT NONE OF THE ABOVE ISSUES APPLY TO MY PROPOSAL	**X**	

5. Consideration of gender aspects

The partnership is quite unbalance with respect to gender equality. This respect the real conditions that are present at every level in every country. Only since few years this issue seems to be taken into higher consideration by the European Community. In the consortium the partnership will be pushed to enclose in the activity and promote in first line female personnel and diffuse the awareness raising as collateral exploitation. Furthermore, they have to stimulate their own institution to adopt actions for gender equality.

"MAINTENANCE OF THE CULTURAL HERITAGE CONSTRUCTIONS FROM THEIR COMPREHENSION AS A WHOLE" - MACH

ANNEX 1

EC FUNDED PROJECTS IN THE FIELD OF CULTURAL HERITAGE

Air pollution threshold levels for cultural heritage:
CARAMEL, MULTIASSESS, CULTSTRAT, **NOAH's ARK***

Damage and restoration on historic buildings and monuments:
ONSITEFORMASONRY, DIAS, ASSET, **COMPASS**, ROCEM, FORTMED, **McDUR**, FIRE- TECH, **HISTOCLEAN**, GRAFFITAGE, **SALTCONTROL, DESALINATION**, CONSIST, SPRECOMAH *, **MOMOREX, CHEF*. CHRAF***

Novel Microbiological Tools for conservation:
COALITION, CATS, BIOREINFORCE, BIOBRUSH, BACPOLES, BIODAM.

Environment inside museums and damage assessment of movable assets:
IMPACT, MIMIC, MASTER, LIDO, VIDRIO, IDAP, MULTIENCODE, PAPYLUM, INKCOR,MIP, MODHT,TEXMED, LASERACT, SURVENIR, PAPERTREAT, FING-ART-PRINT, COLLAPSE, SENSORGAN, COINS, PROPAINT, CONSTGLASS*,AUTHENTICO**

Integration of C.H. in the urban and rural setting, archaeology and cultural tourism:
SUIT, APPEAR, DEMOTEC, HERCOMANES, PICTURE, ARCHAEOMAP*

3D digitalization of artifacts and architectures: -
IST - **ViHAP3D**", NoE IST "**EPOCH**"

(*) Still ongoing - 6FP

PRELIMINARY LIST OF PROJECTS WHOSE RESULTS COULD BE USED IN MACH

- ONSITEFORMASONRY - On-site investigation techniques for the structural evaluation of historic masonry buildings (FP5 EC)**, BAM:** Guideline of the application of radar, active thermography and acoustic methods for the structural investigation of historic masonry, combination of radar and active thermography, damage catalogue. The innovation in the Mach project will be on the quantitative data, data fusion (direct super positioning of data from the same volume recorded with different methods).

- Sustainable Bridges (FP6 EC), **BAM:** Automatic scanner system for radar investigations and for testing of reinforcing laminates with active thermography.

- CHEF Cultural Heritage Protection against Flood **(**FP6 EC**), BAM and ITAM:** Project, which has just been started (Kick Off Meeting in February 2007):.

- Salt Control and Compass (FP5 EC), **TNO:** Theoretical models, investigation techniques, sampling procedures, analysis methodologies, expert systems (MDSS) have been developed in these projects. The knowledge acquired can be adopted and further developed in the framework of the MACH project.

- ViHAP3D - Virtual Heritage: 3D High Quality Acquisition and Presentation (FP5 EC), **ISTI CNR** design of improved software tools for the 3D digitalization of artefacts and architectures, oriented to provide more efficient management tools for the huge 3D models produced with 3D scanning technologies.

- EPOCH -(FP6 EC), a European Research Network on Excellence in Processing Open Cultural Heritage, **ISTI CNR:** Further evolution of software tools for supporting 3D scanning; the distribution of those tools to the CH community for wide dissemination and assessment; the design of new image-based methodologies for 3D models acquisition.

- CULT STRAT (FP6 EC), **-** Assessment of Air Pollution Effects on Cultural Heritage - Management Strategies **ITAM:** Maintenance and restoration costs, life cycles of materials and their treatments.

- Noah's Ark – (FP6 EC) Global Climate Change impact on built heritage and cultural Landscapes **ITAM:** Analysis of the wind flow around buildings and details. Experiments on scaled models including the pressure and wind velocity measurements which served primarily as the prototype for the subsequent numerical models used for parametric studies.

- DIAS - (FP5 EC), Integrated tool for in situ characterization of effectiveness and durability of conservation techniques in historical structures **TUC**, **ICBVC**, **SINT**: Portable, integrated device (DIAS) for in situ reliable and cost-effective characterization of the strength and stiffness of stones. Reference user-friendly database of in situ and in laboratory standard and non-standard (via DIAS) mechanical properties for a wide variety of stones and relevant software of the integrated DIAS system..

ALA/95/23/2003/077-122 "Seismic Resistance of Cultural Heritage Buildings" [2004-2006], funded by the EU-India Economic Cross Cultural programme, **UPC**: Among the deliverables are a "Guidelines for the conservation of historical masonry structures in seismic areas" and a document on "Identification of strengthening strategies".

- MCDUR - Effect of the weathering on stone materials: assessment of their mechanical durability (FP5 EC), **ICVBC**: **TUC, IPPT,** Use of portable instruments (Drilling Resistance Measurement System – Ultrasonic Pulse Velocity – Schmidt Hammer) for the evaluation of the stone durability on stone sample submitted to artificial and natural ageing.

- HISTOCLEAN Intelligent Surface measurement technology for laser cleaning of historic buildings and monuments (FP5 EC), **INNOWEP: ITAM.**

- MOMOREX – (Culture 2000 – CLT- CA12 2003) – **ICVBC**, European façades painted during the XVI century: Model of a project for the monitoring of deterioration subsequent to recent restoration.

-CHRAF (FP6 EC). Priorities and strategies to support Cultural heritage Research Activities within ECTP and future FP7 activities (**UPV/EHU** subcontractor)

ANNEX 2:

PRELIMINARY DOCUMENTS FOR THE STATE OF THE ART:

- DIAGNOSYS OF THE CONSERVATION STATE AND TREATMENT METHODS ON BUILDING MINERAL MATERIALS
Maite Maguregui, Alfredo Sarmiento, Kepa Castro, Juan Manuel Madariaga

- ENVIRONMENTAL AND MECHANICAL BEHAVIOUR OF HISTORICAL BUILDING MATERIALS
Marek Skłodowski, Andrzej Domonik, Arkadiusz Kwiecień, Leszek Małyszko,

- STRUCTURAL AND MATERIAL CHARACTERIZATION OF THE CULTURAL HERITAGE CONSTRUCTIONS
Santiago Sánchez-Beitia,

- NONDESTRUCTIVE TESTING OF WOOD PRODUCTS AND STRUCTURES: STATE-OF-THE-ART AND RESEARCH NEEDS
R. H. Falk, M. Patton-Mallory, and K. A. McDonald

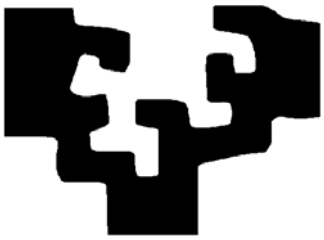
- MONITORAGGIO STRUTTURALE DINAMICO CON FIBRE OTTICHE
Daniele INAUDI, Angelo FIGINI
MOMOREX PROJECT

- MONITORING PAINTED FAÇADES AFTER A CONSERVATIVE INTERVENTION (-Bibliographical survey by S. Serrao, ICVBC)

NOAH'S ARK
- GLOBAL CLIMATE CHANGE IMPACT ON BUILT HERITAGE AND CULTURAL LANDSCAPES
Deliverable 6
Overview of the expected negative and positive consequences of global environmental changes on deterioration of materials (CNR-ISAC)
Deliverable 7
"Scientific reference on mechanical damage and failures of historic structures due to weather effects and related natural disasters and their mitigation strategies and measures" (ITAM)

DEPARTMENT OF ANALYTICAL CHEMISTRY
THE UNIVERSITY OF THE BASQUE COUNTRY

emanta zabalzazu



UPV/EHU

Diagnose the Conservation State and Treatment Methods on Building Mineral Materials

A State of the Art Report prepared by

Maite Maguregui
Alfredo Sarmiento
Kepa Castro
Juan Manuel Madariaga

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INTRODUCTION

Humans have employed stone materials in the construction of their homes from the beginning of time. In fact, primitive men inhabited in caves. Nowadays this kind of materials can be found in the external and internal structures of most of historical buildings.

Stones have been chosen for constructive purposes due to their supposed inalterability and their final cover. Although in the past these materials seemed to be indestructible, today, it is far known that they suffer from several kinds of deterioration processes.

A high proportion of the Cultural Heritage around the world is built in stone and it is slowly but inexorably disappearing.

Experts in the matter have reached the general consensus that in the beginning of the third millennium it would be important to carry out urgent and suitable activities in order to preserve and conserve our Cultural Heritage.

Without any doubt, the first step in any kind of study on this topic is the identification and characterization of the materials presents in the building and the alterations produced over them along the time.

It can be distinguished two fundamental kind of stone decay: natural and artificial. That is, buildings and monuments constructed with different stone materials suffer from alteration processes that are very similar to those observed ones in natural rocks and, at the same time, from specific processes derived from urban environment.

HISTORICAL BUILDINGS DESCRIPTION

Buildings are very complex entities made up of structural, functional and decorative materials that show different behaviour.

Structural materials constitute the framework or the shell of buildings, and in this group it can be found wooden (natural and agglomerated), stone and ceramic materials or, more recently, metals.

Among functional ones, there are materials that cover the top of the structure (tile, aluminium, slate…) while other such as bricks, stones, gypsum or even glass form the walls and the different internal divisions of the buildings. Elements of access, floors, balconies, stairs, chimneys and installations (electricity, pipes, calefaction…) belong to this category of materials as well.

Finally, decorative materials enrich and embellish all constructive elements, especially in the interior of the building. Plated and stone covering can be found in facades, while richer stones, wood, metals, ceramic and polychrome are practically exclusive of the interior decoration.

MATERIALS IN BUILDINGS

Historical buildings have been made with several types of natural materials and used by men in several types of artefacts from very simple mono-components to complex structures integrating inorganic and organic material.

Natural stones were used in the most representative monuments and buildings due to their permanence and resistance to fire. At the same time, the sculpture was integrated in the structure of these architectonic works due to the possibility of stones to be sculpted easily. The use of natural stones in construction is now in decadence especially because of their high cost. Instead, artificial stones such as concrete and glass or lighter materials (like iron) are employed.

In regions that were stone and wood, were not available earth was used as constructive material. That is the origin of mud wall and adobe. The first one consists of a wall of earth or mud packed down, and the second one is a constructive block made of clay and straw, and dried under the sun. Later, bricks and other ceramic products appeared. They are based on firing clay pieces in an oven and they are more resistive than adobe materials.

Construction with stone, brick and other materials is known as masonry. The union of these elements may be reached by the effects of the gravity or through the use of mortar joints. A mortar is a paste composed of sand (or small size stones) and lime (or another binder) combined with some inert substances. Mortars have been used since Roman period.

The buildings constructed with this kind of materials were covered with marble or stuccos (gypsum) to reach a perfect finish. In the 19th century Portland cement was made up. It is completely waterproof and it constitutes the base of the modern concrete.

Construction materials can be classified taking into a count their origin in:

- Stone materials
  - Natural
    - Igneous stones
    - Sedimentary stones
    - Metamorfic stones
  - Artificial
    - Ceramic materials
    - Glases
- Binders
  - Aerial
    - Gypsum
    - Lime
  - Hydraulic
    - Cements
    - Pozzolans
  - Mortars
  - Concrete
- Metallic
  - Ferric
  - Non ferric
- Organic
  - Wood
  - Plastics
- Others
  - Bituminous
  - Paints
  - Insulating materials

In this case only stone and related materials will be considered.

CHARACTERIZATION OF STONE MATERIALS

The characterization of stone materials consists in the description of their main features such as colour, composition, structure, macroscopic and microscopic texture and porosity, among others. Therefore, physical and mechanical tests, chemical analysis and mineralogical and petrographic studies must be carried out on the materials found in the construction of buildings to reach this aim.

The main goals of the building material characterization are preservation and restoration, aiding archaeological studies. The first approach to the investigation of the building is the visual examination of the work and a process of documentation that includes: location, datation, physical identification (environmental description and spatial composition), documental investigation (historical and constructive information, technical studies…) and structural pathologies visible to the naked eye (fissures, cracks…). In this phase of the analyses techniques like photography, scanners and different kind of image analyses are very valuable tools: (a) to record a graphic register of the current state of the building and (b) to compare the obtained images with others (old and future ones) in order to have a global vision of the changes suffered by the building.

After this visual examination, "in situ" analyses are usually carried out. These examinations can give an indication of the stone at that particular moment, generally monitoring the stone decays. NonDestructive Testing (NDT) has become an essential tool in the conservation of artworks and in the preservation of historic buildings. In many cases it is necessary to characterize the underlying strata of an artistic or historic object in order to design the plan of the technical conservation measures, to understand its history, to authenticate it, or to look for hidden features. X-ray and gamma-ray radiography and tomography [1-5] as well as IR imaging and thermography [6-11] have been used in conservation practice for generations. In the last decades, microerosion meter [12], line profilometry, [L. Binda, G. Baronio, B. Lubelli, P. Rocca, Effectiveness of Surface Treatments of Stone and Brick Masonry: Proposal and Calibration of On Site Control Techniques, *8th IBMaC*, Vancouver, Canada, Vol. 1, 1999, pp. 538-549]

texture analysis [13], close-range photogrammetry [14], ultrasonic imaging [15-18], micro-drilling [19], electromagnetic detection [20-23], spectral analysis thermovision [24], endoscopy [25], holographic and laser interferometry [26,27], the electron microprobe [28,29], the laser microprobe [30,31], microwave impulse radar [32,33], eddy current imaging [34] and fiber-optic imaging [35,36] have been also introduced for this purpose.

These techniques let us identify cracks, surface lost, moisture and irregularities of stone materials. In this way it is possible to obtain a model of the whole building. Unfortunately, for mainstream conservation and preservation some of these technologies are too costly and/or difficult to be implemented as a routine analytical tool. In other instances, penetration is too superficial or signals from the depth of interest are masked by interferences. Recently, a new diagnostic device has been introduced into the conservation field. In this case, stone characterization analyses are reported using miniature x-ray devices that can be inserted into cracks and holes in specimens of interest [37].

After establishing the historical and physical significance of the building and assessing and understanding weathering and other decay process affecting the materials, it is time to answer all technical questions by applying the most appropriated analytical techniques on samples taken from the work or building.

Samples can be used to study several aspects of the stone material and its deteriorations. The type of sample preparation, the analyses undertaken and the resulting recommendations will depend on the problem being researched. From the conservation point of view sampling is invasive, and should not be considered a routine procedure. However, in the most cases it is necessary to sampling. Thus, is essential

to obtain representative samples of the stone trying to avoid misinterpretations and incomplete information. Samples should always be taken directly from the building and not from fallen stone from the building.

We can use portable drills with circular crown to obtain cylindrical samples, scalpels and other mechanical samplers to perform the sampling.

Over these samples, petrographic, mineralogical, physical and chemical analysis are carried out.

Petrographic analysis identifies the mineralogical composition of stone materials and the conditions under which has been formed, through the observation of a thin section of the material under a polarizing microscope. This allows crystals and grains (as small as one micron) to be viewed in plane-polaryzed and cross-polaryzed light. In this way, it is possible to determine the type of minerals present and any changes in their composition [38-41].

Physical parameters such as hardness, water absorption, water vapour permeability, capillarity, saturation coefficient, porosity and pore size distribution, granulometry, adsorption isotherms, drying rate, adhesion, resistance to salt crystallization, density or specific weight, moisture, colour, etc., are measured in all samples [42-44].

Besides, an analysis of the mechanical properties of the material is usually done. These properties include impact strength, mechanical resistance, elastic modulus, thermal and hydraulic dilation, test of flexion, compression and torsion and abrasion resistance, among others [45-48].

The petrographic, physical and mechanical properties are usually tested following standard methods developed in different countries to allow accurate characterization of stone materials (ISO, UNE EN, BS EN, UNI EN, CNR, RILEM recommendations etc).

In 1977, with the aim of unifying these methods for studding alterations in stones and in stone-like materials (natural stones, plasters, mortars, bricks, etc.), the NORMAL (Normativa Manufatti Lapidei) Comission was created.

Mineralogical and chemical characterization is achieved making use of a wide range of analytical techniques that they are normally used in a combined way.

Microanalytical and surface techniques have been employed for last decades in the study of stone materials and their mechanisms of decaying. Among them, we could mention the scanning electron microscopy-energy dispersive X-ray spectrometer (SEM-EDS) [49], widely used in this area. This instrument lets explore the surface of a material and makes an elemental analysis of a small area of the sample, but it is not possible to obtain molecular information of the minerals present. Another technique, related to SEM and which use is growing at this time, is electronic microprobe analysis (EMPA) [50].

X-Ray diffraction (XRD), Fourier transform infrared spectroscopy (FTIR) and thermal analysis (TG, DTG, TGA, DSC) have been the most employed techniques to determine the mineralogical composition of stone materials and their decaying products. It must be pointed out that XRD can only be applied to non amorphous samples [51-58].

Other microanalytical techniques such as laser microprobe mass spectrometry (LMMS) [59], X-Ray photoelectronic spectroscopy (XPS) [60, 61], particle induced X-

Ray emission (PIXE) [62] and X-Ray fluorescence (XRF) [63,64] show great possibilities although they have been employed in few works and studies.

The application of secondary ion mass spectroscopy (SIMS)[65] has been explored recently while Auger electron spectroscopy (AES) [60], Mössbauer spectroscopy [66], neutron activation analyses [52,67], and Raman microprobe analysis [68] have been used by few authors up to now.

During last years it is remarkable the use of induced coupled plasma, both with optical detector (ICP-AES) [69] and with mass spectrometer (ICP-MS) [70], in the study of archaeological materials to carry out isotopic and trace element analyses. These last techniques are not routine methods due to their high cost, and for this reason, to carry out elemental analysis, atomic absorption spectroscopy (AAS) [71] is still the most habitual technique.

DETERIORATION OF STONE MATERIALS AND CHARACTERIZATION OF THEIR DEGRADATION PRODUCTS

Before we can take any action to prevent or to remedy the deterioration of stone materials in buildings, we must understand what is causing it. While sometimes, the cause is clear; other times there may be several different causes acting together.

Stone materials decay takes many different forms. The material can weather away gradually, leaving a sound surface behind, or sometimes, large scales of it drop away in one go. In other cases, the surface erupts into blisters; the material loses all integrity and simply crumbles away. In the worst case, it may look perfectly sound to the naked eye, while under the surface it has lost its cohesion.

The possible causes of that phenomena are very varied and include earthquakes, fire, floods, terrorism, vandalism, neglect, tourism, previous treatments, wind, rain, frost, temperature fluctuations, chemical attack, salt growth, pollution, biodeterioration, etc. Some of the mentioned causes are sudden and rapid in their effects. Others, like those toward the end of the mentioned list, are slow and more insidious [72].

A large number of papers have been published concerning the causes of stone materials decay [73-77]. The most mentioned ones are: air pollution, salts and biodeterioration.

- Salts

One of the main reasons for weathering of building stones is crystallization of soluble salts. These may be originally present in the building materials or may have penetrated later in the walls from external sources like ground-water, sea-salt spray, etc.. Dissolved in water, salts flow through a complex stone capillary system towards the stone's surface. Salt can cause damage in building materials through mechanical and chemical processes. Mechanical damage occurs when salts, crystallizing and filling the pores of the material, exert pressures on the pore walls. Mechanical stresses can be exerted also by hydration of the salt and by differential thermal expansion between the salt and the stone matrix. When these stresses exceed the tensile strength of the stone disruption and decay occur.

Chemical damage occurs when components of building materials are transformed, because of the salts, into more soluble compounds (e.g. leaching of lime mortar in marine environment) or when a chemical reaction, made possible by the presence of salts, results into new compounds with larger volume (e.g. Friedel's salt, thaumasite, ettringite formation.

Material damage due to salt crystallization occurs only if salts crystallize in the pore of the materials (crypto-florescences); if salts crystallize on the surface, as efflorescences, no material damage occurs. The location of crystallization is influenced by the substrate's nature, climatic conditions, and salt-system characteristics. Therefore, textural anisotropy, pore size and distribution within the building stone, relative humidity and temperature, and chemistry of the saline system solutions, will control the process which will take place [78].

The types and concentrations of salts found on building stone vary greatly and depend on the stone type and the environment around the building. In general, the most common salts are sulphates, chlorides and nitrates. They include calcium sulphate ($CaSO_4$), sodium sulphate ($NaSO_4$), magnesium sulphate ($MgSO_4$), calcium chloride (CaCl2), sodium chloride (NaCl), potassium chloride (KCl) and potassium nitrate (KNO_3). Calcium and magnesium carbonates or a compound mixture of both (Dolomite $CaMg(CO_3)_2$) can be also present.

Among all these salts, calcium sulphate is generally found in the highest concentrations on stone buildings and is widely thought to be the most damaging agent to stone. It comes from the atmospheric pollution. Accumulation of sulphates, many derived from the oxidation of sulphur dioxide, is of particular concern. Nitrates, which can be originated from the numerous oxides of nitrogen present in the atmosphere (N_2O, NO, N_2O_3, NO_2, N_2O_5) and from different kind of infiltrations (rain water, ground water, irrigation water, etc.) can also be accumulated because they have a high solubility. Then, they migrate from the surface and they are washed away by rain. Thus, unlike sulphates, nitrate accumulation is not a surface phenomenon.

Some author report that Sulfur isotope analyses [79] seem to be a useful tool for the characterization of various sources of sulfur in the natural as well as in the anthropogenic environment relevant to salt formation on monuments and buildings.

Chloride salts are mainly present in the external parts of buildings which are near marine environments but can also come from other sources as de-icing salts, sea-flooding, use of the bulding as salt-storage etc.. The effects of marine aerosols on the stone decay process have caught the attention of researchers [80, B.Lubelli, R.P.J. van Hees, C.J.W.P. Groot, The role of sea-salts in the occurrence of different damage mechanisms and decay pattern, Construction and Building Materials 18 (2), 119-124 (2004)]. The building materials are deteriorate under the action of saline fog which carry out chloride salts, that in combination with movement and evaporation of water forms solutions of soluble salts in the surface of the stone. This pathology is very common in the Mediterranean area [81].

The characterization of the soluble salt presents in stone buildings can be separated in two blocks: mineralogical, petrographycal and thermal characterization of saline efflorescences, and quantification of soluble salts presents in the aqueous extract after a previous extraction step.

For the petrographycal and mineralogical characterization, techniques such as scanning electron microscopy/energy-dispersive (SEM/EDS), X-ray Fluorescence (XRF) [82,83] and spectroscopic techniques (FTIR, Raman spectroscopy) [84-86] have been used. Thermogravimetric and differential thermal analysis (DTA) or simultaneous infrared spectroscopy and thermogravimetrics (TG-FTIR) [87-90] and X-ray diffraction (XRD) [91-95] habe been widely applied to the study of mineral phases of these salt efflorescences.

The quantification of soluble salts in stone materials (stones, mortars, bricks,etc…) needs a previous extraction of salts to the aqueous phase. A classical method for the extraction of soluble salts is the NORMAL 13/83 method [96]. This method consider the following ionic species present in stone materials: SO_4^{2-}, NO_2^-, NO_3^-, Cl^-, CO_3^{2-}, Na^+, K^+, Ca^{2+}, Mg^{2+} y NH_4^+. Other authors add to the previous ionic species list phosphates, acetates, formates, fluorides, etc. The NORMAL method is long and tedious. When many samples must be extracted, this method turn out very long, therefore, an alternative extraction method which gives similar results in a shorter time must be found.

In fact, some authors report alternatives to NORMAL method which are based on the ultrasonic extraction [97,98]. The time for the total extraction of soluble salts in the ultrasonic method is 45 minutes, opposite to the 3 days in the NORMAL method.

The anions (coming from the salts) are usually quantified with ion chromatography [99-103] while cations derived from the salts can be quantified using ICP-MS, AAS or ion chromatography.

A qualitative indication of the salt content can be obtained by measuring the hygroscopic moisture content at a certain RH, higher than the RH of equilibrium of the salts present in the wall [B. Lubelli, R.P.J. van Hees, H.J.P.Brocken, Experimental research on hygroscopic behaviour of porous specimens contaminated with salts, Construction and Building Materials, 18 (5), 339-348 (2004)]

- ❖ Air pollution

Atmospheric gas and aerosol deposition is one of the main processes of environmental degradation occurring on the external surfaces of monuments and historical buildings. Several studies about the effects of environmental conditions on the deterioration of monuments have been carried out [104,105].

One of the most important causes of dirtiness and deterioration of stone materials are processes related to particles or agents coming from combustion of hydrocarbons or pollution in general.

Contamination has influence in the state of materials in two ways:

- o Chemical effect: atmospheric gases react with several mineral compounds giving rise to new substances that precipitate in the surface forming crusts.
- o Physical effect, unchained by solid particles, coming from pollution, that they are placed in the surface of the materials due to the action of wind and rain. They also cause crusts (especially black crusts).

In the case of atmospheric gases there are several kind of aerosol which produced the decaying of stone materials. The atmospheric aerosols react with the

stone materials, especially with the external materials which are more exposed to their effects, giving the decaying compounds and changing the original composition of the masonry.

Most research has focused on the “traditional” pollutants: sulphur oxides, nitrogen oxides, and carbon dioxide. All of them are capable of dissolving in water to give an acidic solution, and thus, they are capable of reacting with stone materials such as limestone, marble, lime mortar, etc. All are naturally occurring, but human activity has greatly increased their amounts [106].

For example, mortar can react in different ways with atmospheric SO_2 and can be formed calcium sulfite hydrate, gypsum, and syngenite [107].

During the last decade, cases of a new form of sulphate attack (the thaumasite form) have been discovered in buried concretes and/or mortars where significant damage of the matrix occurs as a consequence of the replacement of cement hydrates by thaumasite.

A great deal of research, particularly in Italy [108] has been concerned with the nature and the origins of the black crust. These studies have shown that carbonaceous particles, particularly fly ash [109] (particulate pollution resulting from the combustion of fossil fuels in electrical power generation), are responsible for the blackness of the crust. More important, however, is the discovery that the particles are not passive prisoners in the crust: They contain metal oxides that catalyze the oxidation or sulphur dioxide and hence promote formation of the crust.

In the characterization of decaying compounds, the research has fallen into three areas. First, there have been numerous studies carried out on individual buildings [110], coupled with extensive monitoring of pollution levels. They have the advantage of being based on the fundamental problems: the decay of historic stonework in today’s environment. They are certainly the best way of studying the memory effect.

In the investigation of encrustations morphology and with the aim of identifying and quantifying the key elements and compounds associated with the genesis of encrustation, techniques like: optical microscopy (OM), X-ray diffraction (XRD), Fourier transform infrared spectroscopy (FTIR), energy-dispersive-X-ray fluorescence (EDXRF), scanning electron microscopy coupled with energy-dispersive X-ray analysis (SEM-EDS), differential thermal analysis (DTA) and thermogravimetric analysis (TGA) had been employed [111].

In some studies the TC content (total carbon) had been measured in damage layers. These measures include carbonate carbon, organic carbon and elemental carbon. The organic carbon of CT includes the short carbon chain acids, such as formic, acetic, and oxalic acids, whose anions are constantly detected in black crusts, alongside the anions that are typical tracers on anthropogenic pollution. Furthermore, organic compounds from the black crust by gas chromatography-mass spectrometry (GC-MS) had been also analysed [112]. Other anions like sulphates, nitrates, nitrite, fluoride, chlorides, phosphates and oxalates originated due to the atmospheric degradation had been monitorised by ion chromatography (IC) [113].

In the second area of characterization of decaying process due to the atmospheric pollution, there are studies based on the exposure of small samples of unweathered stone. Typically, carousels carrying twenty or thirty samples are exposed

to a range of different environments [114]. In the preparation of sample of mortar, bricks, etc., many variables must be take in a count, like: porosity, firing temperature, proportion of different components in the final result, etc… First of exposing to different environments (urban, rural, marine, etc…) a previous characterization with the mentioned techniques must be done, and after the exposure test, the same methodology for sample characterization must be done.

The third area in which studies has been focused is the simulation of the pollution effects in the laboratory. They are usually based on new stone, but they offer the advantage of being able to create a wide range of closely defined environments. They are well suited to studying interactions between pollutants, as well as the effects of individual pollutants in isolation. Accelerated weathering chambers had been employed simulating different kind of environments. For example, urban atmosphere with a wide variety of aerosols (NOx, SOx…), marine environment with saline fog chamber, etc [115,116].

- Biodeterioration

The settlement of certain organisms (animals or plants) over architectonic works can cause several alterations in stones: (1) Physical damage (abrasion, mechanical stress) (2) Chemical damage (solubilisation, new-reaction products) and, (3) Aesthetical damage (coloured patches or patinas and crusts).

In fact, different kinds of organisms can grow using the mineral components of the stone materials and its superficial deposits. The main consequence of their metabolic activity, such as the excretion of enzymes, inorganic and organic acids, is the dissolution of the substratum. Moreover, the growth and the swelling of some vegetative structures induce physical stress and mechanical breaks.

The principal groups of organism investigated in relation with the biodeterioration of monumental stones are: bacteria [117], lithophilous algae, cyanobacteria [118], lichens [119], actinomycetes [120], fungi [121], plants (lower plants, weeds, mosses and ivy) [122] and animals (arthropods, pigeons, crows, insects, etc.) [123].

Various methods have been used to classify and quantify the micro and macro organisms involved in the biodeterioration processes. The most usual methods are related to microbiological analysis but several analytical techniques have been also employed, essentially in the characterization of the effect of these processes. Among them, it is necessary to emphasize the use of SEM-EDS [124], X-Ray diffraction [125], Raman spectroscopy [126] and HPLC [127].

TREATMENTS OVER STONE MATERIALS

Due to the great number of decaying processes suffered from stone materials and the impossibility of reducing their causes, both natural and anthropogenic ones, the use of treatments over stones, mortars and bricks is necessary.

Two types of treatments can be distinguished. On one hand, several methods, such as cleaning or salt extraction, only try to repair damages suffered from stone

materials. While on the other hand, other treatments, such as superficial ones, are employed in order to protect the materials in a long-term.

❖ Cleaning

Cleaning is one of the first steps considered in the restoration of stone materials. This treatment can help to see the current conservation state of a building because it removes the dirtiness and the damaged materials from the surface. However, the main reason to carry out this treatment is the change of appearance. A dirty building or monument doesn´t look like well preserved and the dirtiness can hide the best architectonical features of the work.

Easy cleaning treatments are usually based on pressure water application or sand and steam blasting, both producing abrasion of the treated surface.

In the field of the elimination of black crusts with pressure water we can find out a patent [128].

A variant of this method has been used in the restoration works of the Valladolid cathedral. In that work water at 90ºC and 120 bars after treatment with NaOH and EDTA has been used [129].

However, a wide variety of authors have emphasized the damage produced with this kind of cleaning treatments: surface loss, soluble salts decompositions or an increment of vulnerability of the stone against the atmospheric pollutants and biological growths.

The search of a dry cleaner of stone surfaces that avoid the use of corrosive materials is a field totally opened to the investigation. In this sense several detergents, which formulation is under patent, can be found [130,131].

1. *Laser cleaning*

Nowadays, laser cleaning is an excellent alternative to the physical abrasion. Its mechanism is very easy: a laser beam impact on surface and the beam energy is dispersed by vaporization of the dirtiness.

When the stone material is dirty, the light is absorbed and the cleaning take place. When the dirtiness has been removed, the light is reflected through the cleaned surface and no more material is eliminated [132].

However, this methodology is expensive and it requires to take high number of safety precautions to avoid possible decaying. In some cases, in addition to laser cleaning, other chemical cleaning methods were employed [133,134].

2. *Salt extraction*

When the effects of salts affect the integrity of the building, frequently salt desalination treatments are carried out. The most employed materials are clay poultices, paper pulp of different kind of celluloses soak in water, etc.

Research on these desalination methods is on going in the EU project Desalination.

In some cases, additives like EDTA, $NaHCO_3$, $(NH_4)HCO_3$, $(NH_4)_2CO_3$(for the surface cleaning) or fungicides for the destruction of the superficial microorganism has been used.

Alternative methodologies to the use of poultices are electrical fields, electrodyalisis membranes or microwaves. However, until this moment conclusive data have not been obtained.

3. *Biological cleaning*

Biological cleaning has been few investigated for the moment. Nevertheless, the use of several kinds of sulphate-reducing bacteria has showed great possibilities in the elimination of sulphates in artworks [135,136]. Inteman S.A. has also developed a new biological cleaner composed of several microorganisms and enzymes that has proved its efficacy in a historical building in Vitoria (Spain).

❖ Superficial treatments

In the 70s and 80s a high number of investigation was carried out with the purpose of obtaining a unique treatment in order to consolidate and protect stone materials.

1. *Water-repellent coatings*

The aim of this kind of surface treatment is the elimination of the new water incorporated over the stone surface, which can act as carrier of salts.

Polyorganosiloxanes [137], alkoxysiloxanes [138], silicones, polyurethanes [139] and fluoropolymers [140] have been used as water-repellent coatings.

To avoid future decay processes in the stone materials, several authors advise the use of hydrofuge substances [141].

A variant of this methodology has been used in the conservation of the Culture House Oquendo Admiral in San Sebastian (Spain). After applying a fungicide and eliminating loose particles with a manual brush, a consolidant and a water-repellent coating based on silyl ester and methylsiloxane [142] is added on the surface. Recent works reported that the most appropriate products are those which have siloxane followed to those which have partially fluorided acrylic resins. On the other hand, products in acrylic base seem to be not suitable to this kind of treatment [143].

However a great number of authors are very reluctant to the use of water-repellent substances. By evaporating water from internal layers, a new crystal growth is produced. As time passes, these new crystals exert so much pressure that can break the protection layer or even cause the mechanical break of the own stone material. This situation may be worse than that caused by environmental decay [144].

Final report EU project “Evaluation of the performance of surface treatments for the conservation of historic brick masonry” edited by R.P.J. van Hees].

2. *Consolidants*

When stone is severely weakened by decay, some kind of consolidation may be necessary to restore the work.

One of the properties that a consolidant must have is the ability to penetrate through the stone. This, in turn, requires a low viscosity and a low contact angle. Next, the consolidant needs to stiffen in order to strengthen the stone. This can be reached

by applying a wax at elevated temperatures, by using a consolidant dissolved in a solvent or by employing a low-viscosity system that undergoes a chemical reaction.

Consolidants are usually applied to the surface of the stone by brush, spray, pipette or by immersion, and are drawn into the stone by capillarity.

The majority of materials that have been tried as stone consolidants have been organic polymers, but two inorganic materials deserve a particular mention: calcium hydroxide (slaked lime) and barium hydroxide.

3. Atmospheric pollution barriers

Water-repellent coatings avoid the incursion of liquid water in the stone material but not the penetration of water in vapour state. Besides, most of these superficial treatments are permeable to other harmful gasses such as SO_2. Until this moment the use of directional membranes has been studied.

In this same sense, colloidal silica and crystal growth inhibitors [146] have been employed as well. Colloidal silica deposits silica particles in the stone pores. The resultant surface is hydrophilic but the passage of water through stone pores is impeded by the presence of silica particles [147].

However, in spite of its great future projection, the viability of this technique has not been tested thoroughly yet.

4. Inorganic surface treatment

Known the chemical composition of the materials to treat, the use of inorganic treatments seems to be less aggressive because its composition is more similar to the stone materials. The two most employed methods are:

- *Ammonium oxalate*

The conversion of $CaCO_3$ in CaC_2O_4 by using $(NH_4)_2C_2O_4$ has give rise to several experiments, especially in Italy [148-150]. The study of the formed oxalate patinas has proved that they protect the surface by forming a thin and compact shell. This fact is due to the larger chemical stability against pH changes that CaC_2O_4 shows over $CaCO_3$. $CaCO_3$ is attacked to pH less than 6 while CaC_2O_4 tolerate even pH lightly minor than 2. The mineral layer formed is chemically compatible with $CaCO_3$.

Moreover, the comparison between the solubility of calcium oxalate and the solubility of gypsum suggest that the ammonium oxalate should be able to transform gypsum into $CaC_2O_4 \cdot H_2O$ owing to a double exchange mechanism.

The function of the oxalate in stone conservation has always been a controversial subject. However, numerous authors rely on the goodness of this methodology [151].

- *Ionic exchange resins*

The application of the ionic exchange technology to the cleaning and protection of historical buildings begin in the 80s in Italy. The most important developments are contained in two patents [152, 153].

In both cases a protector mineral layer is formed over the original one in a non permanent way. This new layer will be attacked by acid gasses while the original layer remains unalterable. Although these treatments suppose an advance since they avoid

the attack to the original material, the formation of black crusts is still a problem when using these methods.

5. Biocides

The control of biodeterioration on works of art is a complex question. The methodologies and products must be chosen taking in mind substrate conditions and species to be treated, standing not to cause negative interference with materials and with low environmental impact.

Physical and chemical methods are mainly adopted. Many studies have been carried out on methods of disinfection and disinfestation, to evaluate effectiveness, toxicity, chemical stability and harmlessness for treated surfaces. Among the physical methods, irradiation and thermal shocks have been proposed.

Chemical methods, employing biocides, are the most frequently used: indoor aerial disinfection and fumigation have been applied, especially in the past.

Biocides must not only kill the growth in the first place, but they must also be resistant to new strains. They must not have any harmful effect on the stone itself, nor must they change its appearance. They must not be washed out by rainfall or destroyed by ultraviolet light, and they must be safe both to the person applying them and to the wider environment.

Over the last ten years controlled atmospheres were proposed as a viable alternative for insect pests eradication. Further research into traditional and alternative treatments should be carried out to obtain as much information as possible to apply more efficient and harmless methods [154].

ASSESSING THE EFFECTIVINESS OF TREATMENTS OVER STONE MATERIALS

It is convenient to divide evaluation procedures into two categories: those that characterize the stone shortly after treatment has taken place, and those that are concerned primarily with monitoring long-term performance.

We have already looked at a number of methods and techniques that are intended to characterize stone materials and to determine the extent of decay. These exams can be applied to stone that has been treated with a consolidant, a surface coating or that has been subjecting to a cleaning treatment to determine whether there has been an improvement in performance [155-158].

Some techniques can assess the extent to which the treatment is reaching certain objectives. If the treatment is based on the use of water repellent coatings, for example, the measurements of contact angle and water absorptions are appropriate. If it is intended to provide protection against acid rain, the measurements of weight loss or salt formation may be necessary.

The logical outcome of this approach is the definition of a set of performance criteria against which a treatment may be judged.

Natural exposure trials provide the only “true” test. They may be carried out in situ on monuments or on small blocks of stone that can be brought into the laboratory at intervals for evaluation. Either way, the trials can only provide information on a limited number of stones, treatments and environments, and it may be many years before reliable information is obtained.

The use of aging tests may help to evaluate the durability of the treatments. Accelerated weathering chambers (UV, moisture, temperature, air pollution, saline fog) are extensively employed to simulate weathering but they introduce yet another source of uncertainty because it is difficult to know if they accurately reflect long-term behaviour [159].

However, it can be very difficult to compare the findings of one researcher with those of another, and there is a need for standardized procedures. As it has been already mentioned, the standardization of test methods has been the objective of both national and international committees. Notable among them are the recommendations of the Rilem (Reunion Internationale des Laboratoires d´Essais et de Recherches sur les Matériaux et les Constructions) 25 PEM (préservation-érosion-monuments) and 59 TPM (traitement des monuments en pierre) Working groups (Rilem 1976, Pien 1991) and the standards published by the Italian Commissione UNI NORMAL.

BIBLIOGRAPHY

[1] Newman R., 1998, "Applications of X - rays in art authentication (radiography , X - ray diffraction, X - ray fluorescence)", Proceedings of SPIE-The International Society for Optical Engineering, 3315 (Scientific Detection of Fakery in Art), 31-41.
[2] Ogura K., Iijima M. and Kuroda Y., 2005, "Buried object evaluating method, underground resources evaluating method, underground waste evaluating method, underground preserved object evaluating method, stratum structure evaluating method, and building interior monitoring method, all using hard x - rays or γ - rays", U.S. Pat. Appl. Publ., 32 pp.
[3] de Oliveira J.M., Martins A.C.G. and de Milito J.A., 2004, "Analysis of concrete material through gamma ray computerized tomography", Brazilian Journal of Physics, 34(3A), 1020-1023.
[4] Cnudde V. and Jacobs P.J.S., 2004, "Monitoring of weathering and conservation of building materials through non-destructive X-ray computed microtomography", Environmental Geology (Berlin, Germany), 46(3-4), 477-485.
[5] McNamara C.J., Perry T.D., Zinn M., Breuker M. and Mitchell R., 2002, "Biodeterioration of concrete and stone", Microbiologically Influenced Corrosion, Proceedings of Corrosion/2002 Research Topical Symposium, Denver, CO, United States,113-121.
[6] Ludwig N., Redaelli V., Rosina E. And Augelli F., 2004, "Moisture detection in wood and plaster by IR thermography (IRT)", Infrared Physics & Technology, 46(1-2), 161-166.
[7] Aydelidis N.P., Moropoulou A. and Theoulakis P., 2003, "Detection of water deposits and movement in porous materials by infrared imaging", Infrared Physics & Technology, 44(3), 183-190.
[8] Moropoulou A., Avdelidis N.P., Koui M. and Kanellopoulos N.K., 2000, "Dual band infrared thermography as a NDT tool for the characterization of the building materials and conservation performance in historic structures", Materials Research Society Symposium Proceedings 591(Nondestructive Methods for Materials Characterization), 169-174.
[9] Moropoulou A., Koui M., Tsiourva Th., Kourteli Ch. And Papasotiriou D., 1997, "Macro- and micro-non-destructive tests for environmental impact assessment on architectural surfaces", Materials Research Society Symposium Proceedings, 462(Materials Issues in Art and Archaeology V), 343-349.
[10] Dorrego J., Luxan M.P. and Dorrego F., 2003, "Damage detection and localization of reinforcement elements in historic buildings with infrared thermography", RILEM Proceedings PRO 32 (International Conference on Advances in Concrete and Structures Volume 1), 567-574.
[11] Clark M.R., McCann D.M. and Forde M.C., 2003, "Application of infrared thermography to the non-destructive testing of concrete and masonry bridges", NDT&E International 36(4), 265-275.
[12] Trudgill S. T., Viles H. A., Cooke R. U., Inkpen R. J., Heathwaite A. L, 1991, "Trends in stone weathering and atmospheric pollution at St Paul's Cathedral , London, 1980-1990", Atmospheric Environment, Part A: General Topics, 25, 2851-3.

[13] Figueiredo C., Figueiredo P., Aires-Barros L., Pina P.and Ramos V., 2005, "Texture analysis of images taken from artificially aged stones: A statistical and structural approach", Restoration of Buildings and Monuments, 11, 235-246.
[14] Hogrefe H., Schroeder J. and Brueggerhoff St., 1993, "Photogrammetric technique for decay mapping of historical stone monuments", VDI-Berichte (1993), 1060(Materialien in Threr Umwelt), 315-22.
[15] Atzeni C., Sanna U. and Spanu N., "Some mechanisms of microstructure weakening in high-porous calcareous stones", Materials and Structures (Dordrecht, Netherlands), 39(5), 525-531.
[16] Moropoulou A., Koui M., Avdelidis N.P. and Achilleopoulos N., 1999, "NDT for materials quality control, environmental impact assessment and management of cultural heritage", Insight (Northampton, United Kingdom), 41(6), 362-365,368.
[17] Parhar G., 2006, "Advances in ultrasound move modality into new fields", Radiology management, 28(2), 34-41.
[18] Montaldo G., Palacio D., Tanter M. and Fink M., 2005, "Building three-dimensional images using a time-reversal chaotic cavity", IEEE transactions on ultrasonics, ferroelectrics, and frequency control, 52(9), 1489-97.
[19] Take Y., 2002, "Micro-drilling of ceramic materials by precise ultrasound working spindle", Kata Gijutsu, 17(3), 41-45.
[20] Niederleithinger E. and Kruschwitz S., "Characterization of moisture- and salt-load in construction material through impedance spectroscopy", Technische Mitteilungen, 99(1/2), 268-273.
[21] Pineda-Pinon J., Manzano-Ramirez A., Prokhorov E., Morales-Sanchez E. And Gonzalez-Hernandez J., 2004, "Impedance spectroscopy of chemically enhanced clays used for adobe construction", High Performance Structures and Materials, 7(High Performance Structures and Materials II), 253-261.
[22] Mihailescu M., Mihailescu A. and Vaireanu D.I., 2003, "A novel electrochemical array used for mapping the water infiltration in buildings", Science and Technology of Environmental Protection, 10(1), 12-16.
[23] Petkovic J., Huinink H.P., Pel L. and Kopinga K., 2004, "Diffusion in porous building materials with high internal magnetic field gradients", Journal of Magnetic Resonance ,167(1), 97-106
[24] Zukjanik J., Pawlowski K. and Rojek W., 1979, "Study of moisture distribution in thick brickwork by neutron and thermovision methods", Badania Nieniszczace Budow, Krajowe Symp., 3rd
[25] Galli C.and Rosano P., 2003, "The restoration of the Sangallo bastion in Fano: researches, surveyings, and conservation techniques", Annali di Chimica (Rome, Italy), 93(11), 927-934.
[26] Biolzi L., Pedala S. and Labuz J.F., 1997, "Mechanical characterization of natural building stone", Geotechnical Special Publication, 72(Degradation of Natural Building Stone), 33-41.
[27] Peiponen K.E., Karppinen V.V.K. and Varonen R., 1986, "The visualization of leakage flow through building cracks by means of holographic interferometry", Optics & Laser Technology, 18(2), 101-2.
[28] Fehr K. and Zurn S.G., 2000, "Determination of CSH-phases by beam-scanning electron microprobe techniques", Applied Mineralogy: In Research, Economy, Technology, Ecology and Culture, Proceedings of the International Congress on Applied Mineralogy, 6th, Goettingen, Germany, July 17-19, 2, 761-764.
[29] Videla H.A., Guiamet P.S.and Gomez de Sarabia S., 2001,"Biodeterioration of Mayan archeological sites in the Yucatan peninsula, Mexico", International Biodeterioration & Biodegradation, 46(4), 335-341.
[30] Leysen L.A., De Waele J.K., Roekens, E.J. and Van Grieken R.E., 1987, "Electron probe micro-analysis and laser microprobe mass analysis of material leached from a limestone cathedral", Scanning Microscopy, 1(4), 1617-30.
[31] Leysen L., Roekens E., Komy Z. and Van Grieken R., 1987,"A study of the weathering of an historic building", Analytica Chimica Acta, 195, 247-55.
[32] Henrich G., 1999, "Modern devices and methods for nondestructive inspection of moisture damage in buildings", Bautenschutz + Bausanierung, 22(7), 39-44.

[33] Maierhofer Ch. and Wostmann J., 1998, "Investigation of dielectric properties of brick materials as a function of moisture and salt content using a microwave impulse technique at very high frequencies", NDT&E International, 31(4), 259-263.
[34] Corneloup G., Moysan J., Garnier V. and Gueudre C., 1996, "Image analysis dedicated to the non-destructive examination of structural materials", Trends in NDE Science and Technology, Proceedings of the World Conference on NDT, 14th, New Delhi, Dec. 8-13, 3 1785-1788.
[35] Moropoulou A., Koui M., Avdelidis N. P. and Achilleopoulos N., 1999, "NDT for materials quality control, environmental impact assessment and management of cultural heritage", Insight (Northampton, United Kingdom), 41(6), 362-365,368.
[36] Moropoulou A., Koui M., Tsiourva Th., Kourteli Ch. and Papasotiriou D., 1997, "Macro- and micro-non-destructive tests for environmental impact assessment on architectural surfaces", Materials Research Society Symposium Proceedings (1997), 462(Materials Issues in Art and Archaeology V), 343-349.
[37] Lovoi P. and Asmus J. F., 2005, "An X-ray microprobe for in-situ stone and wood characterization", Springer Proceedings in Physics, 100(Lasers in the Conservation of Artworks), 353-356.
[38] Koskiahde A., 2004, "An experiential petrographic classification scheme for the condition assessment of concrete in facade panels and balconies", Materials Characterization, 53(2-4), 327-334.
[39] Sabetta T., Bargossi G.M., D'Amico C., Grillini G.C. and Minguzzi V., 2003,"Sandstones, mortars and clay bricks from Palazzo Fava in Bologna (Italy): a mineralogical petrographic study", GeoActa, Volume Date 2001-2002, 1 71-82.
[40] Dreesen R.and Dusar M., "Historical building stones in the province of Limburg (NE Belgium): role of petrography in provenance and durability assessment", Materials Characterization, 53(2-4), 273-287.
[41] "Identifying and sourcing stone for historic buildings repair. An approach to determining and obtaining compatible replacement stone", Technical Advice Note, March 2006, English Heritage Publishing , Swindon
[42] Andriani G. F. and Walsh N., "Texture, porosity and water permeability of calcarenites from Apulia (SE Italy) used as building and ornamental stone", Bulletin of Engineering Geology and the Environment, 62(1), 77-84.
[43] Armienti P., Mazzoni M. and Salvetti S., 2000, "Characterization of Italian stone materials", Informatore del Marmista, 39(467), 24-39.
[44] Alvarez De Buergo M., Fort R. and Gomez-Heras M., 2004, "The Monastery of Ucles (Cuenca, Spain): characterization and deterioration of building materials", Materiales de Construccion (Madrid, Spain), 54(275), 5-22.
[45] Schlimmer M. and Bieker C., 2006, "Procedure for the determination of mechanical characteristics of a structure building component [Machine Translation]", Ger. Offen.
[46] Biolzi L., Pedala S. and Labuz J. F., "Mechanical characterization of natural building stone", Geotechnical Special Publication (1997), 72(Degradation of Natural Building Stone), 33-41.
[47] Mosquera M. J., Benitez D. and Perry S. H., "Pore structure in mortars applied on restoration. Effect on properties relevant to decay of granite buildings", Cement and Concrete Research, 32(12), 1883-1888.
[48] Franzini M. and Lezzerini M., 2002,"The stones of medieval buildings in Pisa and Lucca (western Tuscany, Italy). 4 - "Agnano breccias" from Mt. Pisano", European Journal of Mineralogy, 14(2), 447-451.
[49]Grieger Ch., Hempel R. and Schiekel M., 1997, "Investigation of building materials using SEM and EDX", Journal of Trace and Microprobe Techniques, 15(4), 493-497.
[50] Sanchez-Moral S., Luque L., Canaveras J.C., Soler V., Garcia-Guinea J. and Aparicio A., "Lime-pozzolana mortars in Roman catacombs: composition, structures and restoration" Cement and Concrete Research, 35(8), 1555-1565.
[51] Brunet-Imbault B., Rannou I. and Muller F., 2004, "X - ray characterization of bulk stones from the patina to the depth stone", Journal de Physique IV: Proceedings, 118, 295-300.
[52] Zamudio-Zamudio T. J., Garrido-Alfonseca A., Tenorio D. and Jimenez-Reyes M., 2003, "Characterization of 16th and 18th century building materials from Veracruz City, Mexico", Microchemical Journal, 74(1), 83-91.

[53] Neuzil, Josef, 1984, "The building stones of the National Museum in Prague and the problems of its reconstruction", Acta Universitatis Carolinae, Geologica, 2, 167-89.
[54] Friolo K. H., Ray A. S., Stuart B. H. and Thomas P. S., "Thermal analysis of heritage stones", Journal of Thermal Analysis and Calorimetry, 80(3), 559-563.
[55] Barcina L. M., Espina A., Suarez M., Garcia J. R. and Rodriguez J., 1997, "Characterization of monumental carbonate stones by thermal analysis (TG, DTG and DSC)", Thermochimica Acta, 290(2), 181-189.
[56] Adams J., Dollimore D. and Griffiths D. L., 1993, "Thermal analytical investigation of ancient mortars from Gothic churches", Journal of Thermal Analysis, 40(1), 275-84.
[57] Perez-Alonso M., Castro K. and Madariaga J. M., 2006, "Vibrational spectroscopic techniques for the analysis of artefacts with historical, artistic and archaeological value", Current Analytical Chemistry, 2(1), 89-100
[58] Ballato P., Cruciani G., Dalconi M.C., Fabbri B.and Macchiarola M., 2005, "Mineralogical study of historical bricks from the Great Palace of Byzantine Emperors in Istanbul based on powder x - ray diffraction data", European Journal of Mineralogy, 17(5), 777-784.
[59] Boke, H., Akkurt, S., Ipekoglu, B, 2004, "Investigation of the pozzolanic properties of bricks used in Horasan mortars and plasters in historic buildings", Key Engineering Materials, 264-268, 2399-2402.
[60] Spoto G. and Ciliberto E., 2000, "X - ray photoelectron spectroscopy and Auger electron spectroscopy in art and technology", Chemical Analysis (New York), 155(Modern Analytical Methods in Art and Archeology), 363-404.
[61] Lambert J. B. and McLaughlin C. D., 1976, "The x - ray photoelectron spectroscopy : a new analytical method for the examination of archeological artefacts", Archaeometry 18, Pt. 2 169-80.
[62] Atzori P., Baeri P., D'Innocenzo A., Pappalardo G., Pappalardo L. and Reitano R., 1996, "Fingerprint PIXE method in the identification of the quarries of some lavic material used as building stone from the S. M. Maddalena Church in Buccheri-Sicily", Nuclear Instruments & Methods in Physics Research, Section B: Beam Interactions with Materials and Atoms, 109/110 639-643.
[63] Andersen H. D., Zimmermann H.D., Friis H. and Schnell U., 2000, "Examination of hydraulic lime mortars of medieval churches in Denmark", RILEM Proceedings, PRO 12(International RILEM Workshop on Historic Mortars: Characteristics and Tests, 1999), 37-42.
[64] Cavallo G. and Moresi M., 2005, "Proposal for an analytical sequence aimed at establishing stucco's composition and technique used. Research on samples collected in Southern Switzerland", Proceedings of SPIE-The International Society for Optical Engineering, 5857(Optical Methods for Arts and Archaeology), 585713/1-585713/11.
[65] Anderle M., Bersani M., Vanzetti L. and Pederzoli S., 2006, "State of art in the SIMS (secondary ion mass spectrometry) application to archaeometry studies", Macromolecular Symposia, 238(Macromolecules in Cultural Heritage), 11-15.
[66] Lopez-Arce P., Garcia-Guinea J., Gracia M. and Obis J., 2003, "Bricks in historical buildings of Toledo City: characterisation and restoration", Materials Characterization, 50(1), 59-68.
[67] Konta, J., 1993, "Stone of a Gothic Pieta discovered in Bern: Comparison with Cretaceous marly chert from Prague", Applied Clay Science, 7(5), 357-66.
[68] Perez-Alonso M., Castro K., Martinez-Arkarazo I., Angulo M., Olazabal M. A.and Madariaga J. M., 2004, "Analysis of bulk and inorganic degradation products of stones , mortars and wall paintings by portable Raman microprobe spectroscopy", Analytical and bioanalytical chemistry, 379(1), 42-50.
[69] Welton R. G., Cuthbert S.J., Mclean R., Hursthouse A. and Hughes J., 2003, "A preliminary study of the phycological degradation of natural stone masonry", Environmental Geochemistry and Health, 25(1), 139-145.
[70] Bityukova L., 2006, "Air pollution effect on the decay of carbonate building stones in old town of Tallinn", Water, Air, & Soil Pollution, 172(1-4), 239-271.
[71] Gulec A., Ersen A. and Baturayoglu N., 2000, "Characterization of some mortar samples of Hagia Sophia sampled from the south-west corner and the repair mortars", PACT (Athens, Greece), 59, 177-188.
[72] Price C.A., 1996, "Stone Conservation. An Overview of Current Research" in Research in Conservation, The Getty Conservation Institute, Los Angeles.

[73] Esbert R.M., Montoto M. and Jordaz G., 1991, "Rock as a construction material: durability, deterioration and conservation", Materiales de Construcción, 41, 61-73
[74] Hendry, E.A.w., 2001, "Masonry walls: materials and construction", Construction and Building Materials, 15, 323-330.
[75] Baronio, G., Binda, L., Tedeschi, C and Tiraboschi, C., 2003, "Characterisation of the materials used in the construction of the Noto Cathedral", Construction and Building Materials, 17, 557-571.
[76] Rodríguez Navarro C., Sebastian Pardo E., Doehne E. and Ginell W.S., 1998, "The role of sepiolite-palygorskite in the decay of ancient Egyptian limestone sculptures", Clays and Clay Minerals, 46, 414-422
[77] Amoroso G. and Fascina V., 1983, "Stone decay and conservation. Atmospheric pollution, cleaning, consolidation and protection", Ed. Elsevier .
[78] Doehne, Eric., 2002, "Salt weathering : a selective review", Geological Society Special Publication 20 5(Natural Stone, Weathering Phenomena, Conservation Strategies and Case Studies), 51-64.
[79] Rea, L., 2006, "The effect of building design on indoor climate and on indoor photochemical air pollutant concentrations", WSEAS Transactions on Environment and Development 2(1), 70-77.
[80] Klemm, W., Siedel, H., 2002, "Evaluation of the origin of sulphate compounds in building stone by sulphur isotope ratio", Geological Society Special Publication, 205(Natural Stone, Weathering Phenomena, Conservation Strategies and Case Studies), 419-429.
[81] Fulvio Z., Macrí, F., 1995, "Marine aerosol and stone decay", The Science of the Total Environment 167, 123-143.
[82] Kamh G. M. E., 2005, "The impact of landslides and salt weathering on Roman structures at high latitudes. - Conway Castle, Great Britain: a case study", Environmental Geology (Heidelberg, Germany), 48(2), 238-254.
[83] Benavente, D.; Garcia del Cura, M. A.; Garcia-Guinea, J.; Sanchez-Moral, S.; Ordonez, S., 2004, "Role of pore structure in salt crystallization in unsaturated porous stone", Journal of Crystal Growth, 260(3-4), 532-544.
[84] Steger, W.E; Lunkwitz, R., 1994, "Spectrometric methods in analysis of building materials and building damage", Wissenschaftliche Zeitschrift der Technischen Universitaet Dresden, 43(2), 53-7.
[85] Bakolas, A., Biscontin, G., Moropoulou, A., Zendri, E., 1996, "Salt impact on brickwork along the canals of Venice", Materials and Structures, 29(185), 47-55.
[86] Caner, E. N., Demirci, S., Turkmenoglu, A. G.,1985, "Deterioration of dolomite by soluble salts in Divrigi Great Mosque-Turkey", Actes - Congr. Int. Alteration Conserv. Pierre, 5th, 1 299-305.
[87] Twilley, John., 2006, "Raman spectroscopy investigations of the weathering alteration of a predazzite marble mouflon of the indus Valley Culture", Journal of Raman Spectroscopy (2006), 37(10), 1201-1210.
[88] Mauro, M., Guarini, G.G.T., Dei, L., 1997, Sci. and Technol. Cultur. Herit, 6(1), 35.
[89] Barcina, L.M., Espina, A., Sufírez, M., García, J.R., Rodríguez, J., 1997., "Characterization of monumental carbonate stones by termal analysis (TG, DTG and DSC), Thermochimica Acta 290, 181-189.
[90] Luigi, D., Mauro, M., Bitossi, G., 1998, "Characterization of salt efflorescences in cultural heritage conservation by thermal analysis", Thermochimica Acta 317, 133-140.
[91] Paama, L., Pitkänen, I., Rönkkömäki, H., Perämäki, P., 1998, "Thermal and infrared spectroscopic characterization of historical mortars", Thermochimica Acta 320, 127-133.
[92] Siedel, H., 2000, "Effects of salts on wall paintings and rendering in Augustusburg Castle", Applied Mineralogy: In Research, Economy, Technology, Ecology and Culture, Proceedings of the International Congress on Applied Mineralogy, 6th, Goettingen, Germany, July 17-19, 2000, 2 1035-1038.
[93] Maione, M., Mangani, F., Amadori, M.L., Campagna, M., 2005, "The weathering of natural and artificial stones in the baroque church of S. Pietro in Valle (Fano-Italy)"., Annali di Chimica (Rome, Italy), 93(4), 415-420.
[94] Ioannou, I., Hall, C., Hoff, W.D., Pugsley, V.A.; Jacques, S.D. M., 2005, "Synchrotron radiation energy-dispersive X - ray diffraction analysis of salt distribution in Lepine limestone", Analyst, 130(7), 1006-1008.

[95] Kamh, G. M. E., 2005, "The impact of landslides and salt weathering on Roman structures at high latitudes. - Conway Castle, Great Britain: a case study", Environmental Geology, 48(2), 238-254.
[96] NORMAL , 1983, *"Dosaggio dei Sali Solubili"*, CNR-ICR, Roma, Italy, 13/83.
[97] Iñigo I, Adolfo C., Alonso, R, Vicente-Tavera, S., 2001, "Dissolution of salts crystallized in building materials using ultrasound: An alternative to NORMAL (1983) standard methodology", Ultrasonics Sonochemistry 8(2), 127-130.
[98] Perez-Alonso, M., Castro, K.., Alvarez, M.., Madariaga, J. M., 2004, "Scientific analysis versus restorer's expertise for diagnosis prior to a restoration process: the case of Santa Maria Church (Hermo , Asturias, North of Spain)", Analytica Chimica Acta 524(1-2), 379-389.
[99] Backbier, L., Rousseau, J., 1993, "Analytical study of salt migration and efflorescence in a mediaeval cathedral", Analytica Chimica Acta, 283(2), 855-867.
[100] Gobbi, G., Zappia, G., Sabbioni, C., 1994, "Anion determination in damage layers of stone monuments", Atmospheric Environment, 29(6), 703-707.
[101] Perry, S.H., Duffy, A.P., 1996, "The short-term effects of mortar joints on salt movement in stone", Atmospheric Anvironment, 31(9), 1297-1305.
[102] Gobbi, G., Zappia, G., Sabbioni, C., 1997, "Sulphite quantification on damaged stones and mortars", Atmospheric Environment, 32(4), 783-789..
[103] Borges, C., Caetano, C., Costa Pessoa, J., Fogueiredo, M.O., Lourenco, A., Malhoa Gomes, M., Silva, T.P, Veiga, J.P., 1997, "Monitoring the renoval of soluble salts from ancient tiles by ion chromatography", Journal of Chromatography A, 770', 195-201.
[104] Bravo A., H., Soto A., R., Sosa E., R., Sanchez A., P., Alarcon J. A. L., Kahl, J., Ruiz B., J, 2006, "Effect of acid rain on building material of the El Tajin archaeological zone in Veracruz, Mexico", Environmental Pollution 144(2), 655-660.
[105] Fassina, V., Favaro, M; Crivellari, F., Naccari, A., 2001, "The stone decay of monuments in relation to atmospheric environment", Annali di Chimica 91(11-12), 767-774.
[106] Fassina, V., Favaro, M., Crivellari, F., Naccari, A., 2001, "The stone decay of monuments in relation to atmospheric environment", Annali di Chimica, 91(11-12), 767-774.
[107] Zappia, G., Sabbioni, C., Sauri, M.G., Gobbi, G, 1994, "Mortar damage to airbone sulfur compounds in a simulation chamber", Mater Struct., 27, 469-73.
[108] Sabbioni, C., Zappia, G., 1992, " Decay of sandstone in urban areas correlated with atmospheric aerosol", Water, Air & Soil Pollution, 63 (3-4), 305-316.
[109] Ausset, P., Del Monte, M., Lefevrel, R.A, 1999, "Embryonic sulphated black crusts on carbonate rocks in atmospheric simulation chamber and in the field: role of carbonaceous fly-ash", Atmospheric Environment 33, 1525-1534.
[110] Maravelaki-Kalaitzaki, P., 2005, "Black crusts and patinas on Pentelic marble from the Parthenon and Erechtheum (Acropoli, Athens): characterization and origin", Analytical Chimica Acta 532, 187-198.
[111] Riontino, C., Sabbioni, C., Ghedini, N., Zappia, G., Gobbi, G., Favoni, O, 1998, "Evaluation of atmospheric deposition on historic buildings by combined thermal analysis and combustion techniques", Thermochimica Acta, 321 (1), 215-22.
[112] Sabbioni, C., Zappia, G., Ghedini, N., Gobbi, G., Favoni, O., 1997, "Black crust on ancient mortars", Atmospheric Environment, 32(2), 215-223.
[113] Sabbioni, C., Ghedini, N., Bonazza, A., 2003, "Organic anions in damage layers on monuments and buildings", Atmospheric Environment, 37 (9-10), 1261-1269.
[114] Lanas, J., Sirera, R., Alvarez, J.I., 2005, "Compositional changes in lime-based mortars exponed to different environments", Thermochimica Acta 429, 219-226.
[115] Vale, J., Martin, A., 1986, "Deterioration of a calcareous stone in simulated atmospheres", Durability of Building Materials, 3(3), 197-212.
[116] Martínez-Ramírez, S., Puertas, F., Blanco-Varela, M.T., Thompsom, G.E., 1997, "Effect of dry deposition of pollutants on the degradation of lime mortars", Cement and Concrete Research, 28(1), 125-133
[117] Alakomi H.L., Paananen A., Suihko M.L., Helander I. M. and Saarela M., 2006, "Weakening effect of cell permeabilizers on Gram-negative bacteria causing biodeterioration", Applied and Environmental Microbiology, 72(7), 4695-4703.
[118] Lamenti G., Tomaselli L. and Tiano P., 2003, "Cyanobacteria and biodeterioration of monumental stones", Molecular Biology and Cultural Heritage, Proceedings of the International Congress on Molecular Biology and Cultural Heritage, Sevilla, Spain, Mar. 4-7, 73-78.

[119] Cheng J., Gong Z., Blume H.P. and Cheng S., 2000, "Biodeterioration of buildings induced by lichens", Huanjing Wuran Zhili Jishu Yu Shebei, 1(2), 65-74.
[120] Nuhoglu Y., 2004, "The biodeteriorative action of microorganisms and the effects on stone monuments under air pollution and continental-cold climatic condition in Erzurum, Turkey", Fresenius Environmental Bulletin, 13(7), 591-599.
[121] Owalina B., 2003, "Role of microorganisms in deterioration of natural building stones", Inzynieria Mineralna, 4(1), 39-48.
[122] Altieri A. and Ricci S., 1997, "Calcium uptake in mosses and its role in stone biodeterioration", International Biodeterioration & Biodegradation, 40(2-4), 201-204.
[123] Gaylarde C. C. and Gaylarde P. M., 2002, "Biodeterioration of historic buildings in Latin America", Proceedings - International Conference [on] Durability of Building Materials and Components, 9th, Brisbane, Australia, Mar. 17-20, 2 171/1-171/9.
[124] Nuhoglu Y., Oguz E., Uslu H., Ozbek A., Ipekoglu B., Ocak I. and Hasenekoglu I., 2006, "The accelerating effects of the microorganisms on biodeterioration of stone monuments under air pollution and continental-cold climatic conditions in Erzurum, Turkey", Science of the Total Environment, 364(1-3), 272-283.
[125] Peraza-Zurita Y., Cultrone G., Sanchez-Castillo P., Sebastian E. and Bolivar F. C., 2005, "Microalgae associated with deteriorated stonework of the fountain of Bibatauin in Granada, Spain", International Biodeterioration & Biodegradation, 55(1), 55-61.
[126] Villar- Susana E. Jorge, Edwards- Howell G. M. and Seaward -Mark R. D., 2004, "Lichen biodeterioration of ecclesiastical monuments in northern Spain", Spectrochimica Acta, Part A: Molecular and Biomolecular Spectroscopy, 60A(5), 1229-1237.
[127] "Biodeterioration of building materials like brick and mortar", 1996, DECHEMA Monographien, 133(Biodeterioration and Biodegradation), 177-183.
[128] Schinck H., 1990, "Environmentally safe method for cleaning and/or impregnating artificial or nature sotne, and its uses", Patent Nº CH673114.
[129] Fort R. and Azcona M.C., 2000, "Cleaning stone materials in the Cathedral of Valladolid (Spain)", Materiales de Construcción, 50, 37-50.
[130] Hosokawa T., Ito M., Osawa H. and Ito Y., 2004, "Agents and methods for cleaning buildings and protection from soils", Jpn. Kokai Tokkyo Koho, 31 pp.
[131] Yakovlev G. V. and Yakovleva L. A., 2006, "Detergent composition for cleaning building stone" Russ., 5 pp
[132] Salimbeni R., Pini R. and Siano S., 2001, "High-quality cleaning in conservation of cultural heritage by optimized Nd:YAG laser-induced ablative effects", Proceedings of SPIE-The International Society for Optical Engineering, 4184(XIII International Symposium on Gas Flow and Chemical Lasers and High-Power Laser Conference, 2000), 551-554.
[133] Lanterna G. and Matteini M., 2000, "Laser cleaning of stone artefacts: a substitute or alternative method?", Journal of Cultural Heritage, S29-S35.
[134] Armani E., Calcagno G., Menichelli C. and Rosseti M., 2000, "The Church of the Maddalena in Venice: the use of laser in the cleaning of the façade", Journal of Cultural Heritage, S99-S104.
[135] Ranalli G., Chiavarini M, Guidetti V., Marsala F., Matteini M., Zanardini E. and Sorlini C., 1997, "The use of microorganisms for the removal of sulphates on artistics stoneworks", International Biodeterioration & Biodegradation, 40, (2-4), 255-261.
[136] Cappitelli F., Zanardini E., Ranalli G. Mello E., Daffonchio D. And Sorlini C., 2006, "Improved methodology for bioremoval of black crusts on historical stone artworks by use of sulphate- reducing bacteria", applied and Environmental Microbiology, May 2006, 3733-3737
[137] Deruelle M. And Mignani G., 2002, "Epoxy-and/or carboxy-functionalizaed polyorganosiloxanes for liquid silicone composition waterproofing treatment of building materials", PCT Int. Appl., WO 2001-FR4217 20011227.
[138] Esbert R.M., Grossi C.M., Valdeon L., Ordaz, J., Alonso F.J. and Marcos R.M., 1990, "Laboratory studies for stone conservation at the Cathedral of Murcia", Materiales de Construcción, 40(217), 5-15.
[139] Cozzi E., Guidetti V. And Palzzi S., 1993, "Aqueous dispersions of fluorinated polyurethanes", Eur. Pat. Appl., Application Nº EP 92-115930.
[140] Moggi G., Lenti D. And Ingoglia D., 1990, "Process and compositions for the protection of building materials", Eur. Pat. Appl., Application Nº EP 89-123404.
[141] Aoki T., 1998, "Restoring of stone building materials", Patent Nº JP61270281.

[142] Rodríguez-Maribona I., Zalbide M., García Garmilla F., Ibañez J.A. and Garin S., 1999, "Conservation study of the stone material used in the Culture House of Almirante Oquendo, in San Sebastian", Materiales de construcción, 49, 19-30.
[143] Toniolo L., Casadio F. and Cariati F., 2001, "A key factor in modern protection of historic buildings: the assesment of penetration of water-repellent polymers into porous stone materials", Annali di Chimica (Rome), 91, 823-832.
[144] Miller E., 1993, "Stone consolidation materials", British Museum.
[146] Okamoto K., Yamaguchi Y., and Imanishi H., 1993, "Anticontamination treatment of building stone", Patent Nº. JP 05221745-
[147] Kozlowski R., Tokarz M. And Persson M., 1992, "Gypstop-a novel protective treatment", 7th International Congress on Deterioration and Conservation of Stone, 1187-1196.
[148] Matteini M., and Givannonni S, 1996, "The protective effect of ammonium oxalate treatment on the surface of wall paintings", Painted Facades, Proceedings of the Eurocare Project, Vienna, 95-101.
[149] Matteini M., Moles A. and Giovannoni S., 1994, "Calcium oxalate as a protective mineral system for wall paintings: methodology and analyses", The Conservation of monuments in the Mediterranean Basin, Proceedings of the 3rd International Symposium, Venice, June 22-25.
[150] Matteini M., 1987, "An assessment of Florentine methods of wall painting conservation based on the use of mineral treatments, The Conservation of Wall Paintings", Proceedings of a symposium organized by the Courtauld Institute of Art and the Getty Conservation Institute, London, July 13-16, 137-148.
[151] Di Bonaventura M.P., Del Gallo M., Cacchio P., Ercole C. and Lepidi, A., 1999, "Microbial formation of oxalate films on monument surfaces: bioprotection or biodeterioration?", Geomicrobiology journal, 16(1), 55-64.
[152] Poucahin M. And Medolago L., 1984, "Reforming calcium carbonate in the restoration of stone monuments or the like", Patent Nº EP 127721.
[153] Pizzigoni G. and Parrini P., "Improved cleaning compositions for removing sulfation-damaged areas of carbonatic lithoidal surfaces", 1988, Patent Nº EP 263486, Patent Nº US 5069811 (1991), Patent Nº CA 1295781 (1992).
[154] Nugari M.P. and Salvadori O., 2003, "Biodeterioration control of cultural heritage: methods and products", Molecular Biology and Cultural Heritage, Proceedings of the International Congress on Molecular Biology and Cultural Heritage, Sevilla, Spain, Mar. 4-7, Editor(s): Saiz-Jimenez, Cesareo., 233-242. Publisher: A. A. Balkema, Rotterdam, Neth.
[155] Roig-Salom J.L., Domenech-Carbo M.T.; de la Cruz-Canizares J.; Bolivar-Galiano F., Pelufo-Carbonell M.J. and Peraza-Zurita Y., 2003, "SEM/EDX and vis spectrophotometry study of the stability of resin-bound mortars used for casting replicas and filling missing parts of historic stone fountains", Analytical and Bioanalytical Chemistry
[156] Boiardi L. and Cuppini G., 2003, "Conservative restoration of the Augustus Arch of Fano: cleaning methodology as derived from preparatory analyses and sampling", Annali di Chimica (Rome, Italy), 93(11), 919-926.
[157] Potgieter-Vermaak S. S., Godoi R. H. M., Grieken R. Van, Potgieter J. H., Oujja M. and Castillejo M., 2005, "Micro -structural characterization of black crust and laser cleaning of building stones by micro -Raman and SEM techniques", Spectrochimica Acta, Part A: Molecular and Biomolecular Spectroscopy, 61A(11-12), 2460-2467.
[158] Gobernado-Mitre I., Medina J., Calvo B., Prieto A. C., Leal L. A., Perez B., Marcos F. and de Frutos A. M., 1996, "Laser cleaning in art restoration", Applied Surface Science, 96-98, 474-478.
[159] Moropoulou A., Haralampopoulos G., Tsiourva Th., Auger F. and Birginie J. M., 2003, "Artificial weathering and non-destructive tests for the performance evaluation of consolidation materials applied on porous stones", Materials and Structures (Bagneux, France), 36(258), 210-217.

ENVIRONMENTAL AND MECHANICAL BEHAVIOUR OF HISTORICAL BUILDING MATERIALS

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INTRODUCTION

Masonry is a composite structural material, which consists of units placed on top of each other, laid dried or integrated with mortar. Stones, clay bricks, concrete blocks, among others constitute the units while cement, lime or mud mortar is used to join them.

Masonry's inherent characteristics is its non-homogenous nature as well as the variability of the quality of the construction. It renders difficult any exact prediction of the overall static and seismic response and failure mechanisms. The variability of masonry properties is very high. Even if the same stone or brick type and mortar mix are used, differences in the construction procedure can lead to masonry assemblies with considerably different properties. Lack of homogeneity of masonry structural materials is typical for such structures, as well as uncertainties concerning the type and quality of connections. These parameters lead to large dispersion of the shear and tensile strength of the masonry.

The differences between the masonry constituents, the construction techniques (most of them based on a traditional know how), the structural configurations etc. make masonry an extremely variable structural material. Every historical masonry structure constitutes a unique and genuine problem. Beyond its own material and structural features, the building is also unique because of its historical modifications, actions experienced and existing damage. General solutions or solutions extrapolated from other cases may not be valid. Codes and conventional methods mostly oriented to modern constructions may fail to describe the real behavior and strength of an ancient masonry structure and to actually evaluate its safety.

There exist also problems of transferring knowledge of materials behaviour into risk and live time assessment of real heritage structures. A behaviour of materials which constitute structural elements is not the same as a behaviour of elements made of these materials and the elements behaviour is not the same as the behaviour of a whole structure. However the knowledge about macroscopic masonry behaviour and even more deeper insight into behaviour of constituent materials can be generalized to great extend to form starting point for futher research and "Comprehension of a Monument as a Whole".

ENVIRONMENTAL BEHAVIOUR

The contemporary environment in which the stone element has managed to exist is essentially determined by **climate, industry, geochemistry** and sometimes by **biospheric agents**. In practice their effects cannot be readily separated. In the case of bricks their technology and local clay composition also play also an important role. There is delicate and complex interplay of many factors in practically every case. Nevertheless, these factors can be considered separately.

Insolation or solar radiation.
They can cause failure of some stone types through **thermal expansion and contraction**. Over time the repetitiveness of the heating and cooling process along a stress zones leads to eventual **material fatigue**. Moisture within the brick/stone increases susceptibility to insolation fracture. This concerns sandstones mainly, and is less effective in granites, for instance. **Thermal stress fatigue** is responsible for a variety of fracturing patterns particularly in combination with other factors.[Meiklejohn 1995]

Moisture.
Water penetration is the **main instigator of decay**. Constant **wetting and drying** of the bricks/stones (especially carbonaceous rocks) over the years causes erosion. This is **natural weathering**. Water traveling within the brick/stone, be it gravitational or capillary, generally acquires solutes (mainly chlorides and carbonates). Weathering zones on brick/stone are primarily the result of **solution, hydration, hydrolysis, ion exchange, chelation, oxidation and reduction**, leading to the selective removal of mineral mass. It **affects the shape and decreases the strength** of brick or stone elements. The next form of moisture-induced deterioration seen in bricks and stones is salt-wedging. This is a zone of salt deposition called sub-florescence. These artifacts develop under beneath and parallel to the surface, corresponding to the frequent moisturizing zone. The salt might be magnesium chloride, calcium chloride, sodium chloride, magnesium acetate, magnesium nitrate etc. This kind of deterioration reveals by, **fracturing, crumbling and discoloration**. in salt deposition zone [Cody 1996]. This can lead to the **exfoliation**, affected zone exfoliates and spalls. Another process causing shattering of brick/stone is **freezing and freeze-and-thaw cycles**. Even if the crystallization of water does not cause visible cracking it may accelerate already existing micro cracks by penetrating micro fissures. **Brick and stone fatigue** due to freeze-and-thaw cycles is attributable to either the compression of air sealed off in porous spaces by the ice or by expansion of freezing water itself. **Surface run-off** is another factor implicated in the destruction of brick/stone elements. Where it occurs regularly, the establishment of mosses, fungi and lichens appears. Mineral accretions may be deposited from solute rich solutions. Rainwater usually includes various ions, many of which assist it in converting or dissolving minerals. There is a distinct tendency for such inclusions, which are usually chlorides, sulfates, nitrates, phosphates and bicarbonates and organic acids, to effect a lowering of the pH of atmospheric water.

Biological factors

Non-human biological agents involved in the deterioration of stone elements range from plants through microfauna to cryptogamic, and include **bacteria**. All brick and stone surfaces bear biotic substances. Micro organisms are implicated in the removal of numerous cations from mineral compounds. Not only do such activities contribute to the **weakening of brick/stone fabric** [Berthelin 1988], they also accelerate production of corrosive agents. Their metabolic products may also be corrosive: bacteria utilizing atmospheric nitrogen (converting it to ammonia, or oxidising this to nitrous or nitric acid); those oxidising sulphur to sulphur dioxide and **converting it to highly corrosive sulphuric** acid or the weaker sulphurous acid; those oxidising iron and manganese from minerals; and those affecting silicates and phosphates with organic acids. The **fungi, by producing oxalic or citric acid**, can destroy various minerals **more aggressively than bacteria**. The citric acid of fungi lead to hydrolysis of silicate minerals. **Algae** do not seem to destroy brick/stone surfaces directly, but they can have a damaging effect through their **ability of moisture retention**, and they depend on the presence of moisture. Especially on carbonates, this may effect minor solution in the presence of carbon dioxide. **Mosses** and **lichens** are also effective in **retaining moisture** for extended periods of time. They are also equipped with rhizoids that are used to secure the plant to its substrate and it absorbs water and nutrients from the host (e.g. stone wall or tombstone).

Industrial factors

Dust can be a significant factor in the deterioration of bricks and stones. Dust raised from vehicular traffic can be highly effective in establishing a **dust cover** over the surface of the elements. Dust can comprise carbon rich compounds transported as aerosols in the wind, and settles on buildings. Dust occurs naturally, but human activities accelerate the contamination significantly. While the dust is washed off by rain, it can accumulate in sheltered locations and often becomes incorporated in **surface mineral deposits**. These **atmospheric pollutants** may lead to the **acidification of rain**. A lowering of pH leads to the mobilization especially of iron ions and thus the **destruction of stone varnishes.**

MECHANICAL BEHAVIOUR OF HISTORICAL BUILDING MATERIALS -

In masonry structures we are facing many different materials. Strong unit elements are bricks and stones, while binders are made of various compositions of lime, hydraulic, cementitious or mud mortars, often incorporating hard aggregates of various size. In historical structures travertines, marbles, limestones, sandstones and granites are used. Large part of European heritage is built as brick masonry structures.

All these materials are sensitive to the confining pressure and exhibit increase of strength with increase of pressure. Consequently they show greater strength under compressive loads and a very little tensile strength [Hoffman 1967, Skłodowski 1984]. This feature results from different mechanisms of material failure activated under various stress conditions.

Bricks and stones can be considered more brittle and show less ductile behaviour than mortars. Also their stiffness and compressive strength is much greater than that of mortars.

Depending on their pore structure historical construction materials absorb water, usually in the less amount in the case of stones than in the case of bricks and mortars. Water absorption strongly increase under unfavourable climatic conditions e.g. combined wind and rain actions [Drdacký 2007].

Another important common feature of historical construction materials is their anisotropy which can be seen at the level of unit compounds, but even more at the level of masonry structure which is highly inhomogeneous and which generally exhibits different vertical and horizontal mechanical properties and can be described as heterogeneous orthotropic medium in the case of regular brick masonry or regular block stone structure. In the case of irregular stone masonry more general anisotropic properties are observed. This leads to non-coincidence of stress and strain directions in the structure and difficulties in assessment of the real state of stress.

Next feature generally observed for bricks, stones, mortars and masonry as assembly of this materials is lowering of stiffness with increased load or deformations usually referred to as strain or stress softening behaviour which must be taken into account in analytical and numerical analysis of deformation processes [Lourenço et al. 1997].

Stone and brick materials and the masonry made of them has also intrinsic property of size effect [Carpinteri 1995, Lourenço 1997] which influences the material as well as the global behaviour of the structure elements. Size effects must be taken into account while extrapolating the results of sub-size specimens testing to full scale objects behaviour.

A very important common property of masonry materials is time dependent deformation increase. This time dependent behaviour need to be described by creep and relaxation functions and modelled as material viscosity [Anzani 2000].

Masonry, as a wide range of other brittle materials, show generally special type of behavior under higher strain rates. It has greater dynamic strength then the static one. This is due to the fact that in brittle materials a time dependent interaction between the applied outer stress and the developed damage exists and is connected with internal micro cracking, especially with time of its activation. A crack cannot extend faster than the movement of its crack boundaries allows. Fast loading during an earthquake is the source of increase of

dynamic strength of the masonry, in comparison to the strength characteristic for strain at static loading rate. It should be pointed out that a fast unloading right after the peak stress may lead to internal damage in masonry but not necessarily to its failure.

There are two general models of stone/brick behavior under loading.
If stone is characterized by a **massive, regular and granular structure**, bound by a hard cementation. its main initial destabilization is achieved by **brittle, intragranular fracturing** stimulated by process of **extension of single grains**. Consequently, brittle fracturing is initiated on the contact of high resistance grains, where high concentration of stresses generally occurs. According to the geological lithogenetic classifications, this kind of fracturing is characteristic for **magmatic** (igneous), **sedimentary and exceptionally metamorphic rocks**, where quartz grains appear locally in the direct adjacent position, while the intergranular space is filled with a hard, mostly siliceous cementation. Similar behavior is attributed to **hard ceramic bricks**. Under loading these **structures remain stable for quite long time,** however their **final collapse is rapid** and they practically lose all their strength at the moment with any residual safety.

In the stones, **where grains are either weak and irregular or scattered randomly in a weak cementation**, or in **soft, porous bricks**, the fracturing process is **intergranular, dominated by process of shearing**. The disintegration of structural bindings in stones of such construction **is very slow** (is similar to creep behavior but in short period of time) due to the shearing resistance and uneven fracture surface. Despite the significant role of unstable fracturing processes, the **residual strength after the final collapse of the structure is retained**. This type of fracturing mechanism is characteristic for **carbonate rocks**, especially **organogenic** ones as well as weak **clastic rocks with carbonate cementation, ferruginous-argillaceous** ones and **not crystallized metamorphic rock of carbonate composition** [Pinińska 2001]. The influence of quartz grains and their position as the initial focuses of fracturing under extension and observed recently in different stones[Pinińska 2004] is confirmed by the earlier scientific research of granites from Westerley [Brace 1963, Norii 1985, Coundall 1986] and crystalline marbles[Olson 1976].

Creep

Time dependent behaviour of stones and other building materials manifested as creep of the material is known since many years. What separates behaviour of historical building materials and masonry walls from well known creep phenomena is the low compressive load level which activates dangerous creep mechanism [Anzani 2000, Binda 2001]. Masonry shows "classic" creep behaviour with, roughly speaking, elastic deformation combined with primary creep (when deformations stabilise at some level), secondary creep (constant deformation rate under constant load) accompanied by plastic yield which can last for centuries and the tertiary creep phase which evolves at the end of the second phase and is characterized by rapid increase of deformation rate and eventual failure of the material. But a very important feature discovered just recently shows that the tertiary creep of historical masonry can be activated under load even lower than 50% of theultimate compressive strength of building

materials. Which means that safety limits of historical constructions in Europe, often bearing greater persistent loads, must be seriously reconsidered.

Earthquakes

Masonry structures, especially unreinforced masonry, are extremely vulnerable during earthquakes and have little chance of surviving a strong shake. They have low strength, low ductility, and low energy dissipation capability. Form of masonry and material characteristics play an important role in the seismic performance of these structures. The European Seismological Commission (ESC) classifies masonry structures in seven groups according to their vulnerability.

Type of structure (masonry)	**Vulnerability Class (A B C D E F)**
1. Rubble stone, field stone	**A**
2. Adobe (earth brick)	**A B**
3. Simple stone	**A B**
4. Massive stone	**B C D**
5. Unreinforced, with manufactured stone units	**A B C**
6. Unreinforced, with RC floors	**B C D**
7. Reinforced brick and confined masonry	**C D E**

According to seismic action, there are four main types of masonry failure modes:
1) Out-of-plane wall collapse;
2) Separation of adjacent walls;
3) In-plane diagonal cracking;
4) Cracking due to stress concentrations around openings (doors and windows)

Recent works show more detailed failure mode classifications depending also on regularity of masonry structure (regular, irregular, rubble) [Vasconcelos 2007].

Generally, the corners of any structure are associated with stress concentrations. If the connection between walls is weak, due for example to a poor brick stacking, it can easily fail. As a result, each of the connecting walls becomes an independent structure, which is the worst-case scenario because walls are then supported only at the bottom. An out-of-plane failure mode is very likely to occur under these circumstances. This mode is common when the main direction of the seismic shake is perpendicular to the masonry walls and when they have insufficient transversal supports The out-of-plane wall collapse mechanisms are mostly associated with tensile failure. and they are present when connections between walls fail.

Masonry walls have high stiffness and if inertial loads are adequately transferred to them, they act as the main lateral resistance system. In shear deformation, the loaded diagonal will shorten and the opposite diagonal will be subjected to tension. If the wall strength is exceeded, this will cause diagonal cracking parallel to the shortened diagonal. Because earthquake loads are cyclic the successive action reversal will generate "X" type of cracking. This in-plane behaviour largely depends on the wall aspect ratio.

In the case of masonry, the geometric imperfections and structural faults like the vertical joints between bricks cannot be avoided. Consequently, under the action of compressive forces stress concentration around the corners of bricks occurs. Then in the contact areas between the stressed brick and bed layers in the lime mortar plastic deformations are slowly developing and a phenomenon of stress redistribution is spontaneously released. The danger of cracking of some bricks or occurrence of any faults in masonry is by virtue of this mechanism largely avoided. It is self-protecting mechanism of masonry against long lasting actions and is usually called adaptation. The ductility of mortar is essential in producing the phenomenon of masonry adaptation to the new actions. When

forces are acting for the short time and up to a certain, not very high, level, the induced energy can be dissipated by the plastic deformations of mortar. Higher dynamic load levels generate stresses which cannot be dissipated by yield mechanism or resisted by frictional stresses between mortar and masonry units and hence cracking appears.

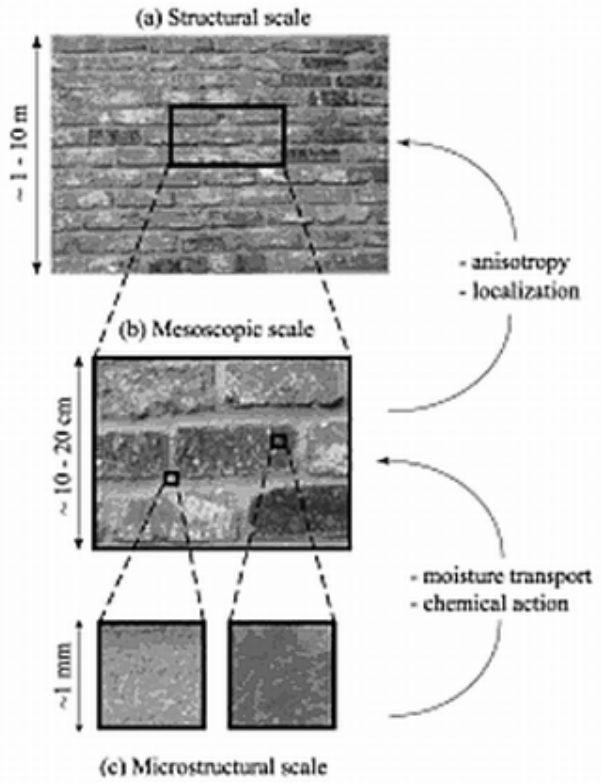
Generally, the buildings made of masonry with porous bricks and lime mortars, support the seismic actions much better than those of masonry with ceramic brick and cement mortars because the probability of stress concentration around structural faults is smaller.

MODELLING OF HISTORICAL MASONRY BEHAVIOUR

The stress distribution in masonry is rather complex depending on the quality of brick and the mortar, the workmanship, the boundary conditions and the applied forces. Therefore assessment of structural safety cannot usually be done without structural analysis in order to estimate the residual strength of the structure and to optimize the consequences of the different repairing techniques.

Theoretical and numerical analysis of masonry materials behaviour is often combined into analytical tool based on the application of the FEM and is widely used with a different degree of complexity (some recent references may be found [4], also cf. [1, 2, 5, 7] among many others). Although the constitutive behaviour of the historical masonry is subjected to various influencing factors, mostly resulting from the complicated microstructure of two basic materials used (units and mortars), for the viable analysis and prediction of the global structural behaviour, a macroscopical approach is required regardless of a type of the loading. Different idealizations can be used – from simply linear elastic behaviour to advanced non-linear behaviour with coupled gradient damage-plasticity. However, masonry, as well as its constituents, is considered as generalized continuum, which obeys constitutive laws obtained by the macroscopic phenomenological approach or by combination of volume averaging of the microscopical process and the attribution of the most prominent features of the global behaviour. The understanding of the physical behaviour of the masonry and its constituents relies on the application and, alternatively, on the formulation of the proper constitutive models at different levels of observation. Moreover, it relies also on the suitable numerical tools, in particular on the discretization methods and efficient algorithms of nonlinear computations for advanced theories of solid mechanics in framework of the finite element method.

The method has several drawbacks. More and more advanced theories of enhanced continuum are necessary to explain and simulate the physical behaviour of heterogeneous materials (materials with microstructure), for which units and mortars are considered. For example, localization and instability phenomena often resulting in failure as well as deterministic size effects observed at the macroscopic level have their origin in meso- and micro-structure of materials which is illustrated in the Figure below.



Representation of the three scales identified in masonry behaviour: (a) structural scale, (b) mesoscopic scale, (c) microstructural scale. The arrows indicate the typical upper scale effects that are caused by lower scale phenomena. Redrawn from Massart [4]

Therefore, the evaluation and robust numerical implementation of enhanced continuum theories are needed (cf., e.g. [5, 6]). Moreover, for the proper description of masonry as a composite material, composed by units and mortars, approaches that are even more sophisticated are required. Difficulties arise especially due to the intrinsic complexity of formulating its anisotropic inelastic behaviour. The homogenisation techniques offer the possibility to use standard material models and software codes for isotropic materials in this respect (cf., e.g. [3, 8]). It is worth to mention, that the facilitation of the description is possible to be done if the total strain can be subdivided into the elastic, creep, shrinkage, thermal and cracking strain. In this way, the constitutive laws for different phenomena can be elaborated independently and the major contributors to time-dependent deformation can be taken into account (cf. [9]). Another silent feature of advanced constitutive models for masonry is a parameter identification problem. Constitutive models contain several material parameters that have to be quantified based on experimental tests. Some of the parameters cannot be determined explicitly from standard or even sophisticated experimental tests. The simultaneous or sequential estimation through parameter identification method must be carried out. Model calibration is an important phase of the theoretical investigation of the constitutive behaviour of masonry and its components. Different inverse procedures for the calibration of the masonry models can be proposed in which the deviations between experimental and theoretical measurements are minimized. Several issues emerge in this kind of process such as the optimal design of experiments, linear or non-linear programming and methods of error treatment in the optimization process or error estimate in the identified parameters as well as the sensitivity and validation analysis of the constitutive model to

various parameters. If the geometrical and mechanical parameters are not considered as deterministic quantities the uncertainties connected to them have to be somehow modelled, e.g. by using fuzzy criterion. In spite of the drawbacks, numerical simulations are a potentially useful tool if they are able to account realistically for the possible failure modes of masonry structures and significant inherent properties of masonry materials.

BIBLIOGRAPHY

1. Berto L. et al.: *Orthotropic damage model for masonry structures.* Int. J. Numer. Meth. Engng. 2002, 55(2), p.127-157.
2. Lourenço P. B. et al.: *Continuum model for Masonry: Parameter Estimation and Validation.* Journal of Structural Engineering, Vol. 124, No 6, ASCE, p. 642 – 652, 1998.
3. Lourenco P.B et al.: *Homogenisation Approaches for Structural Analysis of Masonry Buildings.* Proc. of the 5th Intern. Conf. „ Structural Analysis of Historical Constructions", New Delhi, India, 6-8 November 2006, Vol. 1., p. 59-75, *Macmillan India Ltd. 2007*.
4. Małyszko L.: *Failure modelling in masonry structures taking into account anisotropy.* Rozprawy I Monografie nr 105. *Wydawnictwo UWM w Olsztynie*, pp. 157, Poland 2005 (in polish).
5. Massart T.J.: *Multi-scale modeling of damage in masonry structures.* PhD. Thesis, TU Eindhoven, pp. 152, The Netherlands 2003.
6. Pamin J.: *Gradient-Enhanced Continuum Models: Formulation, Discretization and Applications.* Wydawnictwo Politechniki Krakowskiej, Seria Inżynieria Lądowa, Monografia nr 301, ss. 174, Kraków 2004.
7. Papa E.: *Damage and Failure Models.* In "Computational Modelling of Masonry, Brickwork and Blockwork Structures" Bull J.W (Ed.), p. 1-26, Saxe-Coburg Publications, Stirling, Scotland 2001.
8. Urbański A.: *The Unified Finite Element Formulation of Homogenization of Structural Members with a Periodic Microstructure.* Wydawnictwo Politechniki Krakowskiej, Seria Inżynieria Lądowa, Monografia nr 320, ss. 183, Kraków 2005.
9. Van Zijl G. : *Computational Modelling of Masonry Creep and Shrinkage.* PhD. Thesis, Delft Univ. of Technology, pp. 171, The Netherlands 2000.
10. Pinińska J, 2001, *Systemy geologiczno-inżynierskiej oceny skał i masywów skalnych*. Przegląd Geologiczny, 49, 9.
11. Pinińska J. 2004, *Structural Basis of Compressive extension and shearing mechanism In the Carpathian flysch rocks*. Journal of Theoretical and Applied Mechanics. Vol 2. 315-323. Warsaw
12. Brace W. F., Bambolakis E. G., 1963. *A note of brittle crack growth in compression*. J. Geoph. Res., vol. 68
13. Norii H., Nemat-Nasser S., 1985. *Compression induced microcrack growth in brittle solids: axial splitting and shear failure*. J. Geoph. Res., 90, B-4, Washington

14. Cundall P. A., Fairhurst C., 1986, *Correlation of discontinuum models with physical observations – an approach to the estimation of rock mass behavior*. Felsbau, 4.
15. Olson W. A., Peng S. S., 1976 *Microcrack nucleation in Marble*. Int. J. Rock Mech. Min. Sci. and Geomech. Abstr., 13 London
16. Robert D. Cody, Anita M. Cody, Paul G. Spry, and Guo-Liang Gan *Concrete Deterioration by Deicing Salts: An Experimental Study* Semisequicentennial Transportation Conference Proceedings, May 1996, Iowa State University, Ames, Iowa
17. Berthelin J.. *Microbial weathering processes in natural environments. In A. Lerman and M. Meybeck (eds), Physical and chemical weathering in geochemical cycles*, pp. 33-59. Kluwer Academic Publishers, New York 1988.
18. Meiklejohn K. I. *The deterioration and preservation of rock art in the Kwazulu/Natal Clarens formation: a geomorphological perspective*. Pictogram 8(1), 1995.
19. Hoffman O. 1967. The brittle strength of orthotropic materials.*J. Composite Mat.* 1, 200-206.
20. Skłodowski M., 1984. Influence of the state of stress on the tensile strength of gypsum, *Studia Geotechnica et Mechanica, VI, 3, 43-53.-*
21. Bind L., Saisi A., Messina S. Tringali S. 2001. Mechanical damage due to long term behaviour of multiple leaf pillars in Sicilian churches, in *Structural Analysis of Historical Constructions,* P.B. Lourenço, P. Roca, (Eds.), Guimarães, Portugal.
22. Drdacký M.F., Lesák J., Pospisil S., Slizkova Z. 2007. Tests on gothic sandstone pinnacles subjected to a combined climatic load, in *Structural Analysis of Historical Constructions,* P.B. Lourenço, P. Roca, C. Modena, S. Agraval (eds.), New Delhi 2006, MACMILLAN Advanced Research Series.
23. Vasconcelos G., Lourenço P. B. 2007. Assessment of the in-plane shear strength of stone masonry walls by simplified models, in *Structural Analysis of Historical Constructions,* P.B. Lourenço, P. Roca, C. Modena, S. Agraval (eds.), New Delhi 2006, MACMILLAN Advanced Research Series.
24. European Macroseismic Scale 1998 (EMS-98), Grünthal, G. (ed.), European Seismological Commision, 1998.
25. Sofronie, R. et al., Application of reinforcing techniques with polymer grids for masonry buildings, *CASCADE Report No. 5,* 2005
26. Mayorca P., Navaratnaraj S., Meguro K., Report on the state–of–art in the seismic retrofitting of unreinforced masonry houses by pp-band meches. Tokio 2006.
27. Magnes G., Masonry building design in seismic areas: recent experiences and prospects from an European standpoint. 1th European Conference on Earthquake Engineering and Seismology (1st ECEES), Geneva 2006.
28. Guidelines for the conservation of historical masonry structures in seismic areas. EU-India Economic Cross Cultural Programme. Improving the Seismic Resistance of Cultural Heritage Buildings. Project Contract N°: ALA/95/23/2003/077-122. 2006.
29. Carpinteri A., Chiaia B., Ferro G. 1995. Multifractal scaling laws: an extensive application to nominal strength size effect of concrete structures, *Report no. 51*, Politechnico di Torino, Dipartimento di Ingegneria Strutturale, Turin, Italy.

30. Lourenço P. B., 1997. Two aspects related to the analysis of masonry structures: size effect and parameter sensitivity, *Report no. 03.21.1.31.25*, Delft University of Technology, Delft. The Netherlands.
31. Lourenço P. B., R. de Borst, Rots J.G., 1997. A plane stress softening plasticity model for orthotropic materials. *Int. J. Num. Methods Engrg.*
32. Anzani A., Binda L., Mirabella Roberti G. 2000. The effect of heavy persistent actions into behaviour of ancient masonry, *Masonry and Structures,* vol. 33, n. 228, pp. 251-261.
33. SKŁODOWSKI M., 2007, Quasi-non-destructive testing of historical structural materials using micro-cores, in *Structural Analysis of Historical Constructions, New Delhi 2007. P.B. Lourenço,P. Roca, C. Modena, S. Agraval (Eds) ,860-865, ISBN 972-8692-27-7*.
34. SKŁODOWSKI M., 2006, Micro-cores technology for testing of historical materials, in H*eritage Protection –Cconstruction Aspects, Cavtat 2006, J. Radić, V. Rajčić, R. Žarnić (Eds),205-211, ISBN 953-95428-1-2.*

STRUCTURAL AND MATERIAL CHARACTERIZATION OF THE CULTURAL HERITAGE CONSTRUCTIONS

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1.- INTRODUCTION

In this Report the Structural Characterization means the deduction in situ of the stresses states of the structural elements and the measure of their mechanical properties. Inside this concept these may be included the modelling works. The Characterization of the Structure means the identification of the different components of the constitutive parts in a construction and of their conservation state. The first concept has to be included inside of the Structural Analysis Science. The second intends to deduce the kind of materials, the thickness of layers, connectivity between them, moisture problems, soil state, cracks and strains monitoring, etc… always affecting to the Structural Analysis.

It is necessary to mention that the Characterization of the Structure may affect to the evaluation of a structural state on a construction, in other words to the Structural Characterization. This Report do not intends to include all the techniques and methods to deduce all kind of properties and characteristics of a material or element on Architectural Heritage. This would be non realistic. The characterizations described later are only related with the Structural Analysis. It is possible begin with techniques and properties from a "macroscopic" vision or a "engineering" vision (point of vue). Inside this first approach to deduce the structural state it has to mention the existing techniques or methods to obtain a value of the stresses in situ or the mechanical constants in situ or laboratory. A second step or approach to obtain a structural state is considered in this Report related with the properties or states of conservation which can affect to the structural state. This Report not include other techniques to analyse the biological depositions on surface, other properties (grain size, erosion, thermal and chemical degradations, etc…), chemical compositions and reactions of mortars, … In other words the Report not includes a "microscopic" vision or third approach to obtain a structural state. The influence of this third approach is not considered in this Report. The stylistic or the constructive analysis ("To understand the Monument" concept) surely has more influence in a structural analysis than those properties

2.- STRUCTURAL CHARACTERIZATION

2.1 Stone and brick masonries and steel

There exist three experimental techniques and two analytical methods to obtain the stresses and other two experimental procedures to deduce the mechanical constants "on site".

Experimental Techniques

The Simple Flat Jacks technique allows obtain the vertical stresses in a structural element (stone and brick masonry). There is a RILEM Standard describing the procedure of this technique. The Flat Jacks Technique is very useful for all kinds of materials and it is a procedure widely used. The Technique has a problem because the

cut have to be at least 25 cm deep. This dimension is coincident in many cases with the thickness of the stone blocks in the external layer of a pier or wall. The technique is destructive (in some cases is Minor Destructive) for the element analyzed. In some cases (not standardised) the cut is made smaller but it is not possible to assure that the stresses relax after the cut. The RILEM Standard must be analyzed in depth to obtain a relation between the cut size and the relaxation originated by it.

The Double Flat Jack technique allows the deduction on site of the mechanical constants of a masonry. In this case it is possible to comment the same considerations above mentioned about its character (destructive or not). Recently has been developed the technique of "resistance against drilling" as a parameter related with the mechanical characterisation of a masonry. There is a RILEM Standard about this technique. Perhaps the problem of this technique is the calibration at laboratory of the "resistance against drilling" as a function of the mechanical constants in a masonry. The procedure is a Not Destructive Testing due to the small dimensions of the drill.

The Hole Drilling technique is a old method with a new procedure for the deduction on site of the stresses states (Principal Stresses and their directions). In this moment there is a Spanish Research Project in progress with the objective of to proposing a Standard for its use (already proposed to Spanish Standard Agency). The technique is Minor Destructive because the material eliminated is a round cylinder of 36 mm diameter and 36 mm depth. The method can be used today on stone masonry. For brick masonry analysis there are some problems to solve.

The X-Ray Diffraction Technique is the only method to deduce the stresses states on metallic materials (steel). There is a Standard (ASTM) that establishes the guidelines for its procedure. The X-Ray Diffraction technique is a completely Non Destructive Testing.

Analytical Methods

There are two methods used currently. One of them is widely used and it is based on the FEM scheme. Its application can be employed on different ways. The method has two main problems because the boundary conditions in Architectural Heritage vary with the time and at random. In other words is very difficult to relate the strains of a non continuous material (stone blocks or brick and mortar) with the stress state (behaviour laws). In this moment it is being investigated a specific and not conventional behaviour of the materials and their fracture criteria (creep behaviour and damage functions). These methods are very useful on steels (continuous material). In all the cases the analytical methods have to be checked by laboratory tests. It is not a easy task.

The other method is based on the polygons of forces and on the "funicular" polygons. This method must be related with the appropriate failure conditions and it is very useful for lineal (piers) or bidimensional structural elements (domes, cupolas or vaults). The ancient constructors and others (i.e. the architect Antoni Gaudi) worked with these concepts. The Spanish Research Project above mentioned intends to elaborate a computer application to enable the conventional use of these methods. At this moment its application is laborious; for each case study it one must create the model because computerised databases do not exist yet.

2.2 Wooden structural elements

The experimental methods are based on the extraction of little samples from the structural elements for laboratory tests. The procedure must be Minor Destructive. The samples are tested under tensile or compression loads in order to obtain the mechanical properties of the material (wood). There exist some Standards (i.e. ASTM D143) but currently it is necessary to do some non standardised tests to obtain the mechanical properties. This method is not mentioned in the next Table. Another method for the determination on site of the mechanical properties is based on the "resistance against drilling". The method is Not Destructive Test and may be Minor Destructive. Several laboratories develop research works in order to establish (and propose a Standard) a relation between the "resistance against drilling" and the mechanical constants of the wood. The problem is similar to the mentioned for masonries. The analytical methods can be the classical structural analysis methods or FEM.

2.3. Risk Evaluation

In combination with material data obtained from "characterisation of the structure", the structural analysis schemes are introduced in probabilistic models, allowing calculating the actual safety of the structure. These probabilistic models provide quantifiable reliability factors; on which decisions to conserve, repair or strengthen can be taken.

2.4 Summary

Some techniques were analyzed in the ONSITEFORMASONRY European Project supported by the European Commission (V Framework Programme, finished at 2004). The Table 1 shows a summary of the different techniques and methods mentioned above. The table not includes the methods for extraction of samples for characterisation by means of laboratory tests. Likewise not includes description of these tests.

Table 1. Summary of techniques and their applications

1.- Experimental Techniques →	Simple Flat Jacks	Double Flat Jacks	X-Ray Diffraction	Hole Drilling	Resistance against Drilling	
Materials →	Masonry	Masonry	Steel	Masonry	Masonry	Wooden
Results: -Vertical tresses -Stresses State -Mechanical Constants	Yes	Yes	Yes Yes	Yes Yes	Yes	Yes
Standard	Yes but has to be analyzed	Yes	Yes but has to be analyzed	Next Standard	Yes but has to be analyzed	Yes but has to be analyzed

2.-Analytical Models ▼	Materials →	Masonry	Steel	Wooden
FEM		Yes with precaution	Yes	Yes
Graphical Methods		Very clear		Yes

3.- CHARACTERIZATION OF THE STRUCTURE

The problem was widely researched by the ONSITEFORMASONRY Project above mentioned. Nevertheless it can be affirmed that none technique have got a Standard at this moment. The different research groups use several techniques without a standard that support the procedures and this has to be changed. Nowadays it is possible to use

these research works in order to develop the guidelines for future Standards. The next step must be to propose several Standards for to provide a choice of techniques depending on the case study.

Summary of techniques

3.1.- Ground penetrating radar *(Extracted of the ONSITEFORMASONRY final report)*

The radar method (ground penetrating radar, GPR, impulse radar or radar) as applied in civil engineering is based on the principle of georadar. This technology is already established for more than a half century and successfully used in geophysics for soil investigation. By the development of high frequency antennas as well as of efficient computer systems, it is possible to examine small structures with enhanced resolution. Thus since ten years and more this method can also be applied to building structures. The main tasks are structural investigations of concrete and masonry elements. Since moisture is influencing the dielectric properties of building materials, radar can also be applied to moisture measurements. The radar method is based on the propagation of very short electromagnetic impulses (< 1 ns) having maximum frequencies between 300 MHz and 2.5 GHz for civil engineering applications.

3.2.- Microwave borehole method *(Extracted of the ONSITEFORMASONRY final report)*

The principle of the microwave borehole method is based on the measurement of the absorption of electromagnetic waves between transmitting and receiving antenna in the material to be investigated. From these measured variables and the known thickness of the trough-radiated material the relative permittivity can be calculated, which is dependent on the moisture content of the material. In contradiction to impulse radar, continuous microwaves are generated and measurements are performed at different selected frequencies between 6 and 10 GHz. While the wave passes through the material the wave is absorbed and experiences attenuation. Assuming a homogeneous material the grade of attenuation correlates with the moisture content. To obtain depth resolved information, small transmitting and receiving dipole antennas are moved inside a parallel pair of boreholes.

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3.3.- Geoelectric *(Extracted of the ONSITEFORMASONRY final report)*

The geoelectrical tomography is the reconstruction of the distribution of the electrical resistivities in the body of a structure obtained by current injections across many different couples of electrodes. Two different methods can be used to analyze moisture problems: *transparency tomographies* or *inverted pseudosections* when only one side of the structure is accessible. The *transparency tomographies* use an experimental disposition of the electrodes corresponding to the *cross-hole tomography* in the subsoil: in this case 2 series of electrodes are fixed along 2 profiles on the opposite faces of a masonry structure. The electrodes are connected in different combinations, performing a high number of measurements (typically several hundreds). The cross-section covered by the ray paths is ideally divided into a number of cells (pixels). Their resistivity is computed by means of complex iterative routines. The numerical output (resistivity of

each cell) must be converted into an *image* of the distribution of the resistivities in the cross section to render it into an usable display.

Another technique, the *inverted pseudo-section*, uses only one profile with many electrodes on one face of the structure. Measurements are made with the technique of the so-called *resistivity pseudo-sections* by connecting 4 electrodes at a time with one of the typical arrays used in geoelectrics. A high number of measurements (several hundreds) are performed. The measured data, namely the apparent resistivities, can be directly plotted versus some kind of pseudo-depths to build the so-called pseudo-sections. These are purely qualitative images. By means of a complex inversion process, the distribution of true resistivities versus true depth can be obtained, that is, another kind of geoelectrical tomography. This is sometimes referred as the impedance tomography. In both cases multi-electrode (24, 48 or more) automatic switching geo-resistivitymeters are necessary. Very high quality instruments are required. A particular care must be taken to ensure a good electric contact of the electrodes with the surface of the wall.

3.4.- Impulse-thermography and pulse-phase thermography *(Extracted of the ONSITEFORMASONRY final report)*

3.4.1 Impulse-thermography

Impulse-thermography (IT) is an active approach for a quantitative thermal scanning of the surface of various structures and elements. It has been established as a fast and reliable tool in many areas of non-destructive testing. IT is well known for material testing in miscellaneous industry branches for the detection of voids and delaminations. In civil engineering (CE), the application of thermography was mostly limited to passive investigations of the quality of thermal insulation of building envelopes. In recent years several investigations have been done to apply active thermography to civil engineering. In these investigations the active method has proven its usefulness for locating defects in the near surface region like voids and honeycombing in concrete and delaminations of tiles, plaster and glued carbon fibre reinforced laminates. Further developments and applications in CE are using the sun as a natural heat source, e.g. for the inspections of bridge decks and of paving in general.

3.4.2 Pulse-phase-thermography

A relatively new approach of impulse thermography is the pulse-phase thermography (PPT). It combines the method of data acquisition of the IT with the frequency analysis also used in lock-in thermography. The stored data received during the IT is analysed in the frequency domain via fast Fourier transformation of the transient curve of each pixel in a series of thermal contrast images. This leads to changes in amplitude or phase of the corresponding images. The main advantage of PPT is the information included in the phase images, which are reported to be less influenced by surface infrared and optical characteristics. That also means less sensitivity to non-uniform heating compared with the thermal contrast images of IT.

3.5.- Impact-echo *(Extracted of the ONSITEFORMASONRY final report)*

Impact-echo is a method used for the examination of concrete structures. Typical applications are the determination of the thickness as well as the localisation of cracks, voids, tendon ducts and other inhomogeneities within the structure. The impact-echo can be adapted and optimised for the assessment of masonry structures.

3.6.- Ultrasonics ***(Extracted of the ONSITEFORMASONRY final report)***

Test measurements have shown that it is possible to interpenetrate masonry with a thickness of up to 2.20 m. So it is assumed that it is possible to carry out successful investigations of historic masonry with an unknown structure as well.

3.7.- Sonic method ***(Extracted of the ONSITEFORMASONRY final report)***

The acquiring system is composed by a 6 channels amplifier with an A/D onverter, connected to a laptop; the impulse is given by an instrumented hammer and an accelerometer acquire the signal.

3.8.- Microseismic ***(Extracted of the ONSITEFORMASONRY final report)***

To measure the seismic velocities along profiles a number of transducers are fixed to the surface of the wall. Sonic waves by means of light weight sources are generated at the ends of the profile. The travel times of the seismic waves from the source to each transducer are measured and plotted versus the distance from the source. These graphs are called dromochrones. The slopes of the straight segments of the dromochrones give the velocities of the seismic waves. The seismic refraction profiles may to point out the presence of different materials and eventually crack pattern.

3.9.- Videoscopy ***(Extracted of the ONSITEFORMASONRY final report)***

It is usually applied to visualise the state of inner structural (or not) compounds. The pictures received from the internal faces or areas are recorded with a CCD-chip.

3.10.- X-Ray (Radiological) Inspection

The method is useful in wooden structures to detect metallic elements inside the structural elements, connectivity problems, etc…

3.11.- 2D and 3D Topography

There are optical and laser methods in order to obtain spatial coordinates of points on a Monument. The objective is to create the correct morphology of both the façade and the inner parts of the monuments. Many things can be explained about this procedure. The Laser Topography can be used for other tasks than those mentioned here.

3.12.- Monitoring

The movements on a Construction are a big problem for its future safety. The parameter “time” appear. The cracks growth, settlements in time, progression of strains, etc.. have a big influence on the structural evolution of the elements in Cultural Heritage. The most useful devices contains elements to register the displacements by means of mechanical or electrical methods. The signal can be available for remote analysis.

References

1. Allen D.E., "Limit States Criteria for Structural Evaluation of Existing Buildings. Canadian Journal of Civil Engineering", Vol. 18, No. 6, pp. 995-1004, 1991.
2. Arnjberg-Nielsen and Diamantidis, "Target reliability level for existing structure", Annex A, T2881, Koordination un Entwiklung eines probabilistischen sicherheiskonzepts für neue und bestehende Tragwerke", Fraunhofer, IRB Verlag, 1999.
3. ASRA-net, Advanced Structural Reliability Analysis network http://www.intes.de/asra/asra.html
4. Bea R.G., "Reliability Based Requalification Criteria for Offshore Platforms", Proceedings of ASME-OMAE Conferences, Glasgow, UK, 1993.
5. Binda L., "Flat-jack test as a slightly destructive technique for the diagnosis of brick and stone masonry structures", FORDE, M.C. (Ed.), Abstracts of the Eight International Conference on extending the Life of Bridges, Civil + Building Structures, London, pp. 547-556, 1999.
6. Binda L., Fontana A., Mirabella G., "Mechanical behavior and stress distribution in multiple-leaf walls", 10th International Brick/Block Masonry Conference, Calgary, Canada, 1994.
7. CEB, "Common unified Rules for Different Types of Contruction and Materials", Vol. 1, CEB Bulletin No. 116, 1976.
8. CEB, Comunnauté Europeënne du Beton, "Recommended Target probabilities of failure", CEB model code, 1978.
9. Charter of Krakow, "Principles for conservation and restoration of building heritage", Krakow, 2000.
10. Charter of Venice, "The Venice Charter for the Restoration of Historic Monuments, International Charter for the Conservation and Restoration of Monuments, Gazzola P., Venice, 1964.
11. CIRIA, "Rationalisation of Safety and Serviceability factors in Structural Codes", Report No. 63, Construction Industry Research and Information Association, London, 1977.
12. Claes J. and Hermans K., "Berekeningsmodellen voor metselwerk en metselwerkversteviging", Thesis, Katholieke Universiteit Leuven, 1999.
13. Croci G., "The conservation and Structural restoration of architectural Heritage", Computational Mechanics Publications Southampton, 251 pages 1998.
14. De Raeymaecker L., "Creep Collapse prediction Model for ancient heavily loaded Masonry", Master Thesis, KULeuven-Politecnico di Milano, 2001.
15. Diamantidis D., "Assessment of Existing Structures", Joint Committee of Structural Safety JCSS, Rilem Publications S.A.R.L., The publishing Company of Rilem, 159 pages, 2001.
16. Diamantidis D., "Koordination und Entwicklung eines probabilistischen Sicherheidskonzepts für neue und bestehende Tragwerke", T2881, Fraunhofer IRB Verlag, 1999.
17. Ditlevsen O., "Model uncertainty in structural safety", Structural safety, Elsevier Scientific Publishing Company, Amsterdam, Vol. 1, pp.72-86, 1982.
18. EC1, Eurocode 1, Basis of design and Action on Structures, (1994).
19. EC2, Eurocode 2, "Berekening van betonconstructies – Deel 1-1: Algemene regels en regels voor gebouwen", BIN Belgisch Instituut voor Normalisatie, 1999.
20. EC6, Eurocode 6, Masonry Design, (1995).
21. Egermann R., "Edifici in muratura di pietra; ricerca ed applicazioni all'Universita di Karlsruhe (Germania)", Atti del Convegno Murature, sicurezza, recupero. Relazioni, Trento, pp. 70-95, 1993.
22. Ellingwood B.R, "Reliability_based condition assessment and LRFD for existing structures", Structural Safety, Vol. 18, No. 2, pp. 67_80, 1996.
23. Frangopol D.M. and Kong J.S., "Bridge management based on reliability states and whole life costing: from theory to implementation", Structural Faults and Repair, 2001.
24. Heyman J., The Masonry Arch. Chichester, (1982).
25. Holicky M. and Vrouwenvelder T., "Reliability analysis of a reinforced concrete column designed according to the Eurocodes", Koordination und Entwickelung eines probabilistische Sicherheitskonzepts für neue und bestehende Tragwerke, Fraunhofer IRB Verlag, T2881, pp. 251-264, 1999.
26. Icomos, "Recommendations for the analysis, conservation and structural restoration of architectural heritage", ICOMOS, International Scientific Committee for Analysis and Restoration of Structures of Architectural Heritage, Draft Version n°11, September, 2001.
27. JCSS, General principles on reliability for structural design, IABSE, (1982).
28. Kooharian A., Limit analysis of voussoir (segmental) and concrete arches. Journal of the American Concrete Institute, 24 (4), 317-328, (1952).
29. Larssen H.J. "Determination of partial coefficients and modification factors", International council for building research studies and documentation, Working Commission W18-Timber Structures, CIB-W18/32-1-1, 1999.
30. Lemaire R.M. and Van Balen K., "Stable-Unstable: structural consolidation of ancient buildings", Center for the conservation of historic towns and buildings, KULeuven, Leuven University Press, 344 pages, 1988.

31. Maes M.A., Schueremans L. and Van Balen K., "Reliability based assessment of existing masonry structures", ICASP 8, 8th International Conference on Applications of Statistics and Probability in Soil and Structural Engineering, Eds. Melchers R.E. and Stuwart M.G., Sydney, Australia, pp. 689-695, 1999.
32. Melchers R.E., "Structural Reliability, Analysis and Prediction", Ellis Horwood Series in Civil Engineering, 1999.
33. Montgomery D.C., Design and Analysis of Experiments. John Wiley and Sons, New York, (1997).
34. NEN 6700, "Technische grondslagen voor bouwconstructies - TGB 1990 - Algemene basiseisen", 1991.
35. Remory P., "Thermische vervormting van de toren van Pisa: opstellen van een fysisch model", Master Thesis, Department of Civil Engineering, KULeuven, 98 pages, 1995.
36. Rosiers M., Van Cayseele P. and Van Meerbeek W., "De financiering van de restauratiebehoefte", Brussels, Koning Boudewijn Stichting, 100 pages, 1998.
37. Schaerlaekens S. and Schueremans L., "IWT-project: Restauratie van buitenmuren - Typologie en procedures, deel 3: standzekerheid", Chapter 3, pp. 3/1-3/141, 1997.
38. Schaerlaekens S., De Bruyn R., Van Gemert D. and Schueremans L., "Restauratie van buitenmuren: beoordelen van oud metselwerk", WTCB Tijdschrift, Vol. 2, pp. 3-13, 1999.
39. Schuëller G.I., "Past, Present & Future of simulation-based Structural Analysis", International Colloquium, Euro-Sibram, 2002.
40. Schueremans L., "Probabilistic Evaluation of Structural unreinforced Masonry", Ph. D. Thesis, Department of Civil Engineering, KULeuven, 2001.
41. Schueremans L., Predicting masonry properties from component properties using probabilistic techniques, Strumas 2001, The 5th Symposium on Computer Methods in Structural Masonry, 2001b.
42. Schueremans L., Van Gemert D., "Structureel gedrag. Metselwerk", Handboek Onderhoud, Renovatie en Restauratie, Hoofdstuk II, II.2, pp. 1-50, Kluwer Editorial, 2001.
43. Schueremans L., Van Gemert, D., Smars P., "Safety assessment of masonry arches using probabilistic methods", International Journal for Resoration of Buildings and Monuments, Internationale Zeitschrift für Bauinstandsetsen, Aedificatio Verlag – Fraunhofer IRB Verlag, 2001.
44. Smars P., Etudes sur la stabilité des arcs et voûtes, Ph.d. thesis, KULeuven, Faculty of Applied Sciences, Centre Raymond Lemaire pour la Conservation, Leuven, (2000).
45. Toumbakari E., Van Gemert D. and Tassios T.P., "Multi-blend cementitious injection grouts for repair and strengthening of masonry structures", International Congress Creating with concrete, Dundee 6-10 September, Specialist techniques and materials for Concrete Constructions, Ed. Dhir and Henderson, Thomas Telford, pp. 79-91, 1999.
46. Toumbakari, E.E., "Lime-Pozzolan-Cement grouts and their structural effects on composite masonry walls", Ph. D. Thesis, Department of Civil Engineering, KULeuven, 2002.
47. Valluzzi M.R., "Mechanical behavior of masonry strengthened by lime-based materials and techniques", Ph.D. Thesis, University of Padua, Italy, 2000.
48. Valluzzi M.R., da Porto, F. and Modena, C., "Modeling of the mechanical properties of injected multi-leaf stone masonry walls", Strumas V, International Symposium on Computer Methods in Structural Masonry, Rome, 18-20 April, 2001.
49. Van Balen K., Mateus J., Binda L. and Baronio G., "Expert system for the evaluation of the deterioration of ancient brick structures - scientific background for the evaluation of the deterioration of ancient brick structures", European Community, Energy, Environment and sustainable development, Research report No. 8, Vol. 1, 1997.
50. Van Dyck J., "Probabilistisch Ontwerp", tutorial notes, VTK, KULeuven, (1995).
51. Van Gemert, D., Toumbakari E., Schueremans L., "Konstruktive Injektion von historischem Mauerwerk mit mineralisch- odr polymer gebundenen Mörteln", International Journal for Resoration of Buildings and Monuments, Internationale Zeitschrift für Bauinstandsetsen, Aedificatio Verlag – Fraunhofer IRB Verlag, Vol. 5, No.1, pp. 73-98, 1999.
52. Van Rickstal F., "Grout injection of masonry, scientific approach and modeling", Ph. D. Thesis, Department of Civil Engineering, KULeuven, 2000.
53. Venderickx K., "Evaluatie van geo-electrische metingen op metselwerk", Ph. D. Thesis, KULeuven, Department of Civil Engineering, 1999.
54. Vintzileou E. and Tassios Th., "Three_leaf Stone Masonry strengthening by injecting cement_grouts", Journal of Structural Engineering, Vol. 121, No. 5, pp. 848_856, may 1995.
55. Vrouwenvelder, "Development toward full probabilistic design code", Stuctural Safety, Vol. 24, 2002, pg. 417-432, 2002.
56. Waarts P.H., "Structural reliability using finite element methods", Ph.d. thesis, TU Delft, Netherlands, (2000).
57. Geertsma, J., 1985. Some rock mechanical aspects of oil and gas well completions,. *SPE J.*, 848-856 (1985).

58. Miller, T.W. & Cheatham, J.B., 1964. Analysis of the indentation of a compacting material by a perfectly rough wedge, *Int. J. Rock Mech. Min. Sci.* 9, 475-492 (1964).
59. Papamichos, E, Papanicolopulos, S-A, and Larsen, I., 2006. Springer.Mechanical properties and damage diagnosis of natural building stones. In Fracture and Failure of Natural Building Stones – Applications in the Restoration of Ancient Monuments, S. Kourkoulis (ed.). In Fracture and Failure of Natural Building Stones – Applications in the Restoration of Ancient Monuments.S. Kourkoulis (ed.), Springer.
60. Papamichos, E., Papanicolopulos, S-A., Larsen, I. and Alnæs, L., 2004. Method for in situ, quasi non-destructive diagnosis of mechanical properties and damage of natural building stones Proc. GulfRocks 2004,. *tThe 6th North America Rock Mech. Symp*, *Proc. GulfRocks 2004, Houston.*
61. Santarelli, F.J., Detienne J.L. and Zundel, J.P., 1991,. The use of simple index test in petroleum rock mechanics,. in: *Proc. 32nd U.S. Symp. Rock Mech. 1991.*, Rotterdam: Balkema, Rotterdam, 647-655.
62. Suárez-Rivera, R. Z., Zheng, N.G., Cook, W. and Cooper, G., 1990. Indentation by pore collapse in porous rocks,. in: *Proc. 31st U.S. Symp. Rock Mech. ,1990*. Rotterdam: Balkema, Rotterdam, 671-678.

Thiercelin, M. & Cook, J. 1988,. Failure mechanisms induced by indentation of porous rocks,. in: *Proc. 29th U.S. Symp. Rock Mech.1988,*. Rotterdam: Balkema, Rotterdam, 135-142.

63. Tiano, P., 2003. "The use of microdrilling techniques for the characterization of stone materials. In L.Binda and R.C. de Vekey (eds),*Proceeding of the " rilem tc177 mdt International Workshop on " Site control and non destructive evaluation of masonry structures and materials*",; *Proc. of the Rilem tc177 mdt Intern. Workshop, Mantova (I), 12-13 November. 2001. L.Binda and R.C. de Vekey Eds.*,, Rilem PRO26, 2003, 203-214.
64. Tiano P., Filareto C., Ponticelli S., Ferrari M. and Valentini E., 2000. "Drilling force measurement system a new standardisable methodology to determine the stone cohesion: prototype design and validation". *International Journal for Restoration of Buildings and Monuments, vol 6, n° 2, 2000,* 133-150.
65. Van der Vlis, A.C., 1970,. Rock classification by simple hardness test,. in: *Proc. 2nd Int. Symp. Rock Mech.*, Paper 3-4.

65. Alfes, C., Breit, W., and Schiessl, P., "Hardness testing for the measurement of stone degradation" In "Proceeding of 7th International congress on deterioration and conservation of stone". Lisbon, Portugal, 15-18 June, 1992, vol. 2, 771-780 (1992).

66. Van der Klugt L., Koek J., and Van Hess R. "Some test methods for stone-like materials to be considered for Rilem recommendation"*.* In Evaluation and strengthening of existing masonry structures. Proceeding of the Joint Int. Workshop RILEM TC 127 MS and CIB W 23, 1995. L. Binda and C. Modena Eds. University of Padua Publisher, 143- 152
67. ASM Handbook : "Non destructive Evaluation and Quality Control", vol. 17 (Materials Park, OH: ASM, 1992).
68. Tiano P., Filareto C., Ponticelli S., Ferrari M. and Valentini E., "Drilling force measurement system a new standardisable methodology to determine the stone cohesion: prototype design and validation". *International Journal for Restoration of Buildings and Monuments*, vol 6, n° 2, 2000, 133-150.
69. Tiano P., Delgado Rodrigues J., De Witte E., Verges-Belmin V., Massey S.,. Snethlage R, Costa D., Cadot-Leroux L., Garrod E., and Singer B. "The conservation of monuments : a new method to evaluate consolidating treatments". *International Journal for Restoration of Buildings and Monuments*, vol 6, n° 2, 2000, 115-132.
70. AAVV. Proceedings of the EC Workshop DRILLMORE, Munchen (D) March 16-17/2000. P. Tiano Ed. CSOA, Firenze (I). Marzo 2000.
71. G. Exadaktylos, P. Tiano, C. Filareto, "Validation of a model of rotary drilling of rocks with the drilling force measurement system". *International Journal for Restoration of Buildings and Monuments*, vol 6, n° 3, 2000, 307-340.
72. Tiano P., Viggiano A.*, "A new diagnostic tool for the evaluation of the hardness of natural and artificial stones*" International Journal for Restoration of Buildings and Monuments, vol 6, n° 5, 2000, 555-566.
73. J. Delgado Rodriguez and D. Costa "*A New Method for Data Correction in Drill Resistance Tests for the Effect of Drill Bit Wear"* International Journal for Restoration Internationale Zeitschrift für Bauinstandsetzen Vol. 10, No 3, 1–18 (2004)
74. Van Balen, K.: Weaker may be better: insights into the durability of lime, http://www.kuleuven.ac.be/bwk/materials/Research/KVB/GCI_2/GCI_2.htm
75. Cikrle P., Drdácký M., Lesák J., Slížková Z., Untergutsch A., Válek J., Vavřík D. and Zíma P.: Small sample testing, Final report of the FP5 EC project EVK4-2001-00091/ EVK4-CT-2001-00060 "ONSITEFORMASONRY".

76. Drdácký, M., Michoinová, D., Procházka, P.P.: Lime mortars reinforced with fibres for restoration and safeguarding of cultural heritage (in Czech - Maltovinové směsi vyztužené vlákny pro obnovu a záchranu uměleckých památek), Research report ITAM CAS, December 2002, 146 pages
77. Drdácký, M.F., Michoinová, D.: Lime mortars with natural fibres, in Proc. Int. Symp. "Brittle Matrix Composites 7", A.M.Brandt, V.C.Li and I.H.Marshall, eds., ZTUREK RSI and Woodhead Publ., Warsaw 2003, pp. 523-532
78. Vavřík, D., Drdácký, M.: Experimental determination of stress-strain dependence for thin fibres, Book of Extended abstracts & CD ROM "Engineering Mechanics 2003", National Conf. with Int. Participation, Svratka, May 12-15, ISBN 80-86246-18-3, ITAM CAS CZ, Prague, 2003
79. Kasal, B., Drdácký, M., Jirovský, I.: Semi-destructive methods for evaluation of timber structures, in: Proceedings STREMAH VIII, Series: Advances in Architecture, Vol. 15, pp. 835-842, WIT Press, ISBN 1-85312-968-2, 2003
80. Drdácký, M., Jirovský, I., Slížková, Z.: On structural health and technological survey of historical timber structures, in Procedings "Conservation of Historic Wooden Structures" (G.Tampone, ed.), Vol.1, pp.278-284, Collegio degli Ingegneri della Toscana, Florence, 2005
81. Doležel, T., Drdácký, M., Konvalinka, P., Kopecký, L.: Experimental analysis of sandstone and travertine, Acta Polytechnica, Vol.44, No.5-6, pp. 89-92, 2004
82. Slížková, Z.: Development of hydraulic binder based on metakaolin, (In original Czech: Vývoj směsného hydraulického pojiva na bázi metakaolinu), in Proceedings "Rehabilitation of Monuments 2004"(Obnova památek 2004), Axis, 2004.
83. Standard Test Method for Determinig Residual Stresses by the Hole-Drilling Strain-Gage Method. ASTM 837-95 Standard. American Society for Testing Materials.
84. Standard Test Method for Determinig Residual Stresses by the Hole-Drilling Strain-Gage Method. ASTM 837-01 Standard. American Society for Testing Materials.
85. Barrallo J, Zulueta A, Blanco L, Caro J, Sánchez-Beitia S. Stress measurements on ancient structures by the hole drilling method. Experimental Techniques (SEM) 1994; 19 (3): 9-13.
86. Barrallo J, Zulueta A, Sánchez-Beitia S. The Donostia Method for stress measurements in architectural heritage. STRAIN (British Society for Strain Measurement) 1999; 35 (3): 107-112
87. Barrallo J, Zulueta A, Sánchez-Beitia. The Hondarribia City Walls. In Brebbia C, Sánchez-Beitia S, editors. Proceedings of STREMAH 97. Donostia-San Sebastián, 1997. p. 559-565.
88. Barrallo J, Zulueta A, Sánchez-Beitia S. El Método Donostia en torno a los 20 kg/cm2 (In spanish). Ingeniería Civil 2002; 125: 113-123
89. Sánchez-Beitia S. Análisis de sistemas portantes en Patrimonio Arquitectónico: relación entre los elementos constructivos y la transmisión de cargas (In spanish). Txertoa Ed. Donostia-San Sebastián 2003.
90. Sánchez Beitia S. Stresses analysis at the Altes Museum of Berlin by means of the Hole Drilling Technique (Donostia Method). Construction and Buildings Materials. Elsevier Ed.
91. Standard Test Method for In Situ Compressive Stress Within Solid Unit Masonry Estimated Using Flatjack Measurements. ASTM C 11Standard. American Society for Testing Materials.
92. Sánchez Beitia S. Stress Analysis of the Piers of the Tarazona Cathedral (Zaragoza-Spain) by means of the Hole-Drilling Technique. Construction and Buildings Materials. Elsevier Ed..
93. Andreu, A., Gil., L., Roca, P. A new deformable cable element for the analysis of cable net structures. Computers & Structures 84 1882-1890 (2006)
94. Oliveira, D. V., Lourenço, P. B., Roca, P. , Cyclic behaviour of stone and brick masonry under uniaxial compressive loading. Materials and Structures, 39 (2) pp. 219-227 (2006)
95. Lourenço, P.B., Oliveira, D.V., Roca, P., Orduña, A., Dry joint stone masonry walls subjected to in-plane combined loading, J. Struct. Engrg., ASCE, 131(11), pp. 1665-1673 (2005)
96. Roca, P. Simplified models for the assessment of masonry shear walls. Construction and Building Materials, 20, pp. 229-238 (2005)
97. Roca, P. Molins, C. Marí. A. R. Strength capacity of masonry wall structures by the equivalent frame method. Journal of Structural Engineering ASCE 131(10), pp. 1601- 1609 (2005)
98. Roca, P., Andreu, A., Gil, L. Analysis of masonry constructions by means of catenary cable networks, Theory, Technique, Valuation, Maintenance. Editura Mediamira, Bucharest, pp. 21-28 (2005)
99. Roca, P., Clemente, R. Studies on the origin of deformation and damage in long-span historical structures. 11th Internacional Conference on Fracture. Torino, (2005)
100. Roca, P., Molins, C (Editors) . Arch Bridges IV. Advances in assessment, structural design and construction, ISBN 84-95999-63-3. Center for Numerical Methods in Engineering (CIMNE), Barcelona, pp. 1-765 (2004)
101. Roca, P., Molins, C. (2004) Experiments on arch bridges. Arch Bridges IV. Advances in assessment, structural design and construction, CIMNE, Barcelona (2004)
102. Massanas, M., Roca, P., Cervera, M., Arun, G. Structural analysis of Küçük Ayasofya Mosque in Ístanbul. Structural Analysis of Historical Constructions IV, Balkema, Amsterdam (2004)

103. Roca, P. Considerations on the significance of history for the structural analysis of ancient constructions. Structural Analysis of Historical Constructions IV, Balkema, Amsterdam (2004)
104. Roca, P. Structural Monitoring of three Gothic Cathedrals . On-site control and evaluation of masonry structures. RILEM Publications, Bagneux, France, pp. 105-118 (2003)
105. Andreu, A., Gil, L., Roca P. .Analysis of masonry skeletal structures by computer simulated funicular models. Computer methods in Structural Masonry-5, Computers & Geotechnics LTS, Swansea, pp. 206-213 (2003)
106. Da Porto, Roca, P., Araiza, J. C. Assessment of load bearing walls through dynamic tests. Performance of construction materials in the new millenium, Elmaarefa Printing House, Cairo, pp. 1227-1235 (2002)
107. Roca, P., González, J. L., Aguerri, F., Aguerri, J. I. Monitoring of long-term damage in Gothic Cathedrals. Structural Studies, Repairs and Maintenance of Heritage Architecture VIII, WIT Press, Southampton, pp. 109-119 (2003)

NONDESTRUCTIVE TESTING OF WOOD PRODUCTS AND STRUCTURES: STATE-OF-THE-ART AND RESEARCH NEEDS

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INTRODUCTION

Though much of the research on nondestructive testing and evaluation has focused on manufactured materials such as metals. polymers, ceramics, and concrete, many applications have been found for the use of non-destructive testing techniques in the inspection and evaluation of wood products and structures. In the case of existing wood structures, these techniques are used for in-place material property determination and detection of decay. In the case of new wood products, nondestructive methods are often used for process control, quality assurance measurements, and grade classification (during and after processing).

Nondestructive techniques have also found application in the evaluation of existing wood buildings and built-up components and in the periodic inspection of other essential facilities and structures such as wood utility poles, cooling towers. dock piling and piers, scaffold planks, and mine timbers.

This paper overviews nondestructive testing research as it is applied to wood products and structures and discusses areas of research needed to more fully utilize this technology. Specifically. the discussion includes acoustic techniques such as sonically and ultrasonically induced stress waves, acoustic emissions. and acousto-ultrasonics. Other methods, including optical scanning, electrical resistance, and those relying on the ability of wood to transmit waves in the form of x rays or microwaves. are discussed. Methods incorporating mechanical vibration characteristics, such as transverse vibrations, are also included.

BACKGROUND

Wood has been used for thousands of years as a construction material for dwellings. ships, and bridges. While availability and ease of work-ability have historically made wood a logical choice for construction, more recent uses are inspired by its low cost and high strength to weight ratio compared with metals and cementous materials.

In: doe Reis, Henrique L.M., ed. Nondestructive testing and evaluation for manufacturing and construction: Proceedings of conference; 1988 August 9-12; Champaign, IL. New York: Hemisphere Publishing Corp.; 1990: 137-147.

Because the material properties of wood are not tightly controlled by ita natural manufacturing process. these properties exhibit inherent variability. The presence of natural defects such as knots, splits, and checks, and the wide diversity of species available for various end uses, add to this variability.

Wood is a material with orthotropic material properties. The structural properties of a wood member depend not only on its orientation when cut from a log, but also on the distribution, size. and shape of the strength-reducing characteristics within the piece and the cellular makeup of the clear wood, which varies between species. The environmental conditions in which wood is used are very important because moisture content of the wood dramatically affects its mechanical properties and its susceptibility to degradation by decay. As a result of these factors, users of wood have long recognized the need to grade or assess quality of wood building materials before they are used in construction.

Nondestructive evaluation (NDE) of wood has been performed for generations. Visual inspection for strength-influencing characteristics has been traditionally used to grade wood into end-use categories. This assessment of wood quality is based only on the size and distribution of anomalies that can be seen on the surface of the lumber. Using this technique, strength-reducing characteristics and species are empirically related to member tensile, bending, or compression performance.

Machine stress rating (MSR) has evolved as a means of measuring and evaluating mechanical properties (strength and stiffness) of lumber (Hoyle 1968, Logan 1978). This nondestructive technique is based on the fact that a beam in bending will deflect in proportion to its average modulus of elasticity (MOE) when subjected to a known load. Lumber bending strength and other properties are then empirically related to MOE by species class. Visual grading and MSR have received considerable research attention and are well established in the solid wood products industry.

In addition to solid wood products, many flake, particle, fiber. and veneer products have been developed that are a combination of wood and adhesive. Following the development of these products there has been a growing need for NDE methods for grading and quality assurance. These methods usually involve identifying internal voids undetectable by visual means, such as "blows" in particleboard. These methods are also used for sorting veneers in the manufacture of parallel laminated veneer lumber.

The concept of "sound" wood has been used for generations to describe another basic form of NDE--aural assessment. Often used to assess the condition of wood utility poles, this method relies on the ability of an inspector to recognize sound patterns, produced by hammer blows, that

are indicative of the presence of decay. Besides being rather subjective, this method is limited by the rather limited frequency range perceptible by the human ear. the upper limit of which is about 20 kHz. In response to this limitation, research has incorporated the use of electronic sensors.

Electronic sensors containing piezoelectric crystals are sensitive to much higher frequencies of sound vibration, and mechanical accelerometers are available for detecting lower frequency sound vibrations. These sensors replace the human ear and serve as the basis of most acoustic techniques used for NDE of new wood products for quality assurance and for the in-place evaluation of wood structures.

NONDESTRUCTIVE EVALUATION METHODS BASED UPON ACOUSTIC MEASUREMENTS

Differences in terminology exist in the literature on acoustic methods applied to the nondestructive testing of wood. Though referred to by several names, such as sonic stress waves, ultrasonic stress waves, ultrasonics, and ultrasonic pulse methods, these methods rely on the theory of acoustic wave propagation and usually differ only in the mode and frequency of excitation. Typically. these methods incorporate two sensors to determine wave speed, the first at one location on the member used to start a timer and the second at another location on the member used to stop the timer. Some devices include signal processing hardware for time and frequency domain analysis.

The basic theory of acoustic wave propagation in a solid material incorporates the fact that energy storage (wave speed) and energy dissipation (damping or attenuation of the wave) characteristics are controlled by the same mechanisms that determine the mechanical properties of the material (Jayne 1959).

Sound Velocity Techniques

The determination of wood material properties using acoustic wave propagation has attracted considerable research effort. Bertholf (1965) described the use of elementary stress wave theory for the prediction of dynamic strain in wood. Galligan and Courteau (1965) applied this theory for the measurement of MOE in structural lumber by inducing stress waves and measuring wave passage time. This work lead to the use of sonic stress wave velocity as a predictor of MOE, modulus of rupture (MOR, ultimate bending load capacity), and other material parameters (Kaiserlik and Pellerin 1977, Pellerin 1965, Ross and Pellerin 1988, Vogt 1985).

A high correlation (correlation coefficient of about 0.90) has been observed between stress wave velocity predictions of MOE and bending MOE from bending tests. It is more difficult to predict MOR using stress wave velocity because the presence (and location) of defects (such as knots) and the slope of grain have a significant effect on MOR but much less of an effect on longitudinal stress wave velocity over the length of a typical piece of structural lumber. Because the defects in wood affect the straightness of the grain (fiber direction) in the wood. any method that is sensitive to the slope of grain has high potential for assessing the strength of wood. Gerhards (1980) investigated the

effects of crossgrain on stress wave velocity and found that wave speed varied by as much as 1% per degree of grain angle up to about 30° . This study concentrated on local measurements with respect to grain deviations.

Using stress wave velocity measurements, Bucur and Archer (1984) determined the elastic compliance matrix for various species of wood. Shear moduli, Young's moduli, and Poisson's ratios for the longitudinal, radial. and tangential directions of the wood correspond to various coefficients of this matrix.

The relative change in moisture content of wood as it dries is reported to be well correlated with the speed of ultrasonic pulses (James et al. 1982). This fact has potential as a means to monitor and affect control of the drying process of wood.

Stress wave velocity measurements have been used to predict material properties in a variety of wood products including structural composite lumber. particleboard. roof and floor sheathing, floor underlayment. and medium density fiberboard (Ross and Pellerin 1988). Jung (1979) suggested stress wave grading techniques for use on veneer sheets used in the manufacture of parallel laminated veneer (PVL). Increases of 30% in allowable bending stress are being realized by sorting PLV strips using stress wave measures of MOE.

Stress wave velocity measurements have also been used to locate the presence and extent of decay in wood members. Hoyle and Pellerin (1978) used a sonic stress wave device to identify areas of decay in two school buildings constructed with glued–laminated timber arches. Areas of decay were successfully mapped out in the wooden arches by comparing stress wave velocity measurements from nondecayed portions of the arches to those from decayed portions. This correlation between perpendicular–to–grain (radial and tangential) stress wave velocities and levels of decay has been further investigated by Rutherford (1987). who found that stress wave velocity measurements could be used to predict about 80% of the variability in MOE for decayed and nondecayed portions of the wood.

Nondestructive tests on a wood barn by Lanius et al. (1981) compared two methods, sonic stress wave velocity measurements and visual grading. Visual–grading estimates of strength and stiffness and those based upon stress wave measurements were compared statistically. It was found that the stress wave method yielded mean material property estimates comparable to the visual grading technique. Additionally, the authors noted the importance of the stress wave measurements in detecting low–strength members.

Acoustically based NDE devices have found widespread use in the electric power industry and are used to monitor the structural condition of wood utility poles subject to the degradative effects of decay and insect attack (Hiller et al. 1965, Shaw 1978, Arita and Kuratani 1984). Bulleit and Falk (1985) worked with the power industry to investigate the use of stress wave velocity measurements to distinguish between strength–reducing decay and non–strength–reducing growth ring separations (ringshake). Using the results of field test measurements and finite element model analysis, they concluded that stress wave velocity measurements alone were not sufficient to confidently differentiate between ringshake and decay.

These acoustic NDE devices have also been useful in the inspection of marine pilings subjected to marine borer attack and decay (Walden and Trussel 1963, Pellerin 1978, Agi 1978, Aggour et al. 1984). Using a procedure similar to wood utility pole inspection, increases in wave passage time attributable to damaged wood are compared with a baseline time measurement for undamaged wood.

An ultrasonic stress wave device has been investigated for use in the detection of straight-grained wood in lumber to provide information for cutting decisions (McDonald 1978). Utilizing a pulsed, 500 kHz transducer and a 1 MHz receiver to propagate sound through wood. this patented (McDonald and Cox 1972) through-transmission technique locates all internal and surface defects that are associated with local grain-angle changes and includes location of decay or rotted wood. Using water as a couplant between the wood and the sensor, the device has been shown to function adequately for hardwood and softwood species, rough-sawn or planed, and green or dry lumber of thicknesses up to 4 in.

Application of sound velocity techniques for in-place wood structures has seen limited implementation because of the important coupling requirements necessary for proper signal transmission. Improvements in transducer construction and the development of self-coupling transducers may improve the utility of these techniques.

Acoustic Emission Techniques

Most of the failure modes that occur in wood are fracture-type mechanisms that emit high-frequency sound energy. Each release of sound energy is typically referred to as a burst of acoustic emission (AE). These brittle-type failure processes begin with microscopic fractures, particularly at stress concentrations around naturally occurring defects or those resulting from the manufacturing process. Acoustic emission techniques have been used extensively as NDE tools for materials other than wood. Typically, the material being evaluated is subjected to a proof load while the quantity and location of AEs are measured.

Although most of the research in utilizing AEs from wood has focused on damage occurring during destructive testing. recent research by Groom and Polensek (1987) shows that bending strength, proportional limit load, and ultimate bending deflection of lumber could be predicted with some accuracy through AE measurements below the proportional limit. Porter et al. (1972) evaluated use of AEs to assess quality of finger joints in wood products. It was concluded that the rate of AEs generated just beyond the proportional limit of the material was a reasonable predictor of finger joint strength.

Wood decay within a structural member causes significant loss of strength before one can visually detect the presence of decay. Beall and Wilcox (1987) used AE techniques to quantify the level of incipient decay in wood members by monitoring AEs during a compression test of small blocks of wood loaded in the radial direction. The specimens with early decay were found to begin emitting sound energy at a much lower load than the nondecayed control specimens.

As research progresses toward understanding the mechanisms that generate AEs during destructive tests of wood products, the technology will

become more useful for NDE of in-place wood members. For example. many types of chemicals are applied to wood to enhance its behavior for a particular end use. Some chemical treatments, such as those used for fire retardancy, are suspected to have a degrading effect on wood strength if subjected to temperatures in the range of 150 to 180°F. Monitoring AEs while testing the treated wood may provide a useful index of damage resulting from these treatments.

Waveform Analysis Techniques

There is considerably more information available in the acoustic waveform received through a material than is contained in the velocity measurements previously described. High-frequency sound waves (20 to 300 kHz) that pass through a material are influenced by the properties of the material. Acousto-ultrasonics is a technology that combines the AE analysis of the received waveform with ultrasonic pulsing technology. A typical system uses resonant sensors. Acousto-ultrasonics can be used in either a through-transmission or a one-sided mode. Both the time and the frequency domains of the received waveform are evaluated in a relative sense. using measurements such as waveform ringdown counts, measures of average signal level (root mean square, RMS), peak amplitude, and frequency content.

Patton-Mallory et al. (1987) used multiple waveform characteristics to distinguish decayed wood from nondecayed wood under controlled conditions in the laboratory. Dunlop (1983) analyzed the velocity and damping characteristics of longitudinal compression waves to evaluate deterioration in wood utility poles. The technique indicated that wood decay influences attenuation to a greater degree than it influences wave velocity.

Beall (1987) evaluated waveform RMS to successfully monitor glueline curing of a wood adhesive connection and found RMS to increase proportionally with the curing of the adhesive. Lemaster and Dornfeld (1987) used acousto-ultrasonics in an effort to detect knots in lumber. decayed wood. grain orientation, and wood moisture content. They concluded that the laboratory technique looked promising for detecting knots, decayed wood. and a range of grain orientations. The results were inconclusive for detecting moisture content changes. The acousto-ultrasonic technique is still evolving and may have an important role in future evaluation of wood structures after additional research is undertaken.

NONDESTRUCTIVE EVALUATION METHODS BASED ON VIBRATIONAL MEASUREMENTS

While transverse vibrational techniques have been used to assess the material properties of wood members in bending (Pellerin 1965) and have lead to the development of commercially available grading devices, recent efforts have been directed towards a better understanding of the time and frequency domain characteristics of longitudinally induced acoustic signals. Sound wood of a particular geometry has characteristic damping properties that influence the propagation of different frequencies of sound or vibration. The measurement of energy storage or energy loss can be made in the time or frequency domain. Depending on

the method used, lower frequency (0 to 20 kHz) or higher frequency (20 to 350 kHz) ranges are analyzed.

Wang (1980) investigated the change in the fundamental mode of frequency for wood specimens exposed to decay fungi by measuring their vibrational characteristics. Increasing levels of decay exposure dramatically reduced the stiffness of the specimens and hence lowered the fundamental mode of frequency.

Modal analysis techniques have also been used for the determination of in-place wood utility pole stiffness and strength (Murphy et al. 1987). This technique monitors the frequency content of the pole and utilizes the fact that stronger and stiffer poles vibrate at higher frequencies than do poles degraded by wood decay. Frequency content can be related to pole condition and hence to expected remaining life.

Additional research is needed in this area to correlate the vibrational characteristics (energy storage and energy dissipation) of the wood member with its stiffness and strength while accounting for the presence of knots, splits, grain deviations, incipient decay, and other defects.

OTHER NONDESTRUCTIVE EVALUATION METHODS APPLIED TO WOOD

In addition to acoustically based NDE methods, a number of other techniques have been applied to the evaluation of wood and wood structures. Many NDE systems have been developed and implemented for the NDE of wood products in a myriad of applications before, during, and after processing from logs to finished wood products. Included are the use of microwaves. x rays, lasers, optics, and digital images. A brief summary of these applications follows.

Microwaves have been used to detect defects in wood products based on wave sensitivity to density changes and grain direction. Using a rotating microwave transmitter, the grain angle at the surface of wood has been measured under laboratory conditions (James et al. 1985). Application of the technique, however, will require additional research to account for the interaction between density and moisture content effects.

The surface grain angle of wood can be measured by two other methods. One uses an electrical capacitance technique to obtain the grain angle based on the dielectric constant of wood. which is about 1.5 times greater along the grain than across the grain (McDonald and Bendtsen 1985). The other is an optical measurement using a laser light source and detectors to measure the variations in the intensity of light, reflected from the wood surface to sense grain direction and other defects (Soest 1987).

X-ray tomography, also known as computerized axial tomography (CAT), uses a photon source and an array of receivers to measure the absorption of gamma rays. This technique is capable of determining internal dam— in wood (Ellinger et al. 1979, Funt and Bryant 1987) and has found application mainly in the detection and location of internal defects in round wood material, such as logs, poles. and pilings. Defects located include knots, cracks, worm holes, and decay.

Nuclear magnetic resonance (NMR) imaging of logs has been explored (Chang et al. 1987, Hailey and Swanson 1987), with positive results that are predicted to have an impact on future NDE applications of assessing the internal quality of wood. Digital images of slices of logs have shown the internal wood structure and defects in detail. Pattern recognition techniques will be necessary to automate the interpretation of such images for future application. Practical application of these commonly used medical devices for wood evaluation is limited by high cost end by the lack of portability necessary to test in-place structures.

Several optic systems have been developed for sensing and locating surface defects on lumber surfaces for grading processing decisions (Connors et al. 1987, Godinez 1987, Wallis 1987). These systems collect reflected light from the board surface or process analog or digital images from which pattern recognition algorithms obtain the defect infomation. Surface quality and acceptable blemishes are variables that must be given serious attention with these systems when transferring the technology to the production line.

RESEARCH NEEDS

This discussion indicates there are several nondestructive test methods that are being used for the evaluation of wood products and structures. However, many of these techniques cannot be fully utilized until more information is available to help interpret NDE measurements.

Specific areas of need are in relating NDE parameters to wood material properties and estimates of remaining life. This is especially important in the case of degraded wood. When estimating or predicting the strength of a piece of wood. it is known that flaws often cause failure. Techniques that can reliably and economically detect the presence of flaws will be considered useful in evaluating the strength of members. Research is also needed to bridge the gap between the known presence of a flaw, or decayed area, and the calculated strength or lifetime prediction.

Quality assurance and quality control procedures are emerging areas requiring research. Particularly for wood composite products and built-up wood members, reliable methods are needed to determine adhesive-to-wood bond strength and to assess mechanical properties for chemically treated wood materials. The challenge of NDE of wood products is enhanced by the natural variation found in this unique building material that is manufactured by nature.

LITERATURE CITED

Aggour, M. S., Ragab, A. M., White Jr., E. J., Determination of In-Place Timber Piling Strength, Transportation Research Record 962, Univ. of Maryland, College Park, pp. 69-77, 1984.

Agi, J. J.. Nondestructive Testing and Structural Analysis of In-Place Wood Marine Piling, Proceedings of the Fourth Nondestructive Testing of Wood Symposium, Washington State University, Pullman, WA, 1978.

Arita, K., and Kuratani, K., Wooden Pole Tester: For Determining the Strength of Decayed Poles, Japan Telecommunications Review, Nippon Telegraph and Telephone Public Corp., Tokyo, Japan, pp. 167-173. July 1984.

Beall, F. C., Wilcox, W. W., Relationship of Acoustic Emission during Radial Compression to Mass Loss from decay, Forest Prod. J. 37(4): 38-42, 1987.

Beall, F. C., Acousto-Ultrasonic Monitoring of Glueline Curing, Wood Fiber Sci. 19(2): 204-214, 1987.

Bertholf, L. D., Use of Elementary Stress Wave Theory for Prediction of Dynamic Strain in Wood, Bulletin 291, Technical Extension Service, Washington State University, Pullman, WA, 1965.

Bucur. V. and Archer, R. R., Elastic Constants for Wood by an Ultrasonic Method, Wood Sci. Technol. 18: 255-265 (1984).

Bulleit, W. M., and Falk, R. H., Modeling Stress Wave Passage Times in Wood Utility Poles, Wood Sci. Technol. 19: 1983-191, 1985.

Chang, S. J., Wang, P. C., and Olson, J. R., Nuclear Magnetic Resonance Imaging of Hardwood Logs. Proceedings 2nd International Conference on Scanning Technology in Sawmilling, Oakland/Berkeley Hills, CA, IX-1-IX-8, Oct. 1987.

Connors, R. W., Klinkhachorn, P., McMillin, C. W., Franklin. J. P.. Ng, C., A Computer Vision System for Grading Hardwood Lumber, Proceedings 2nd International Conference on Scanning Technology in Sawmilling. Oakland/Berkeley Hills, CA, XV-1-XV-7, Oct. 1987.

Dunlop, J. I., Testing of Poles by Acoustic Resonance, Wood Sci. Technol. 17: 31-38. 1983.

Ellinger. H., Morgan, I. L., Klinksiek, R., Hopkins, F., and Thompson, J. N., Imaging Applications for Automated Industrial Inspection and Assembly. Proceedings of the Society of Photo-Optical Instrumentation Engineers, Washington, DC, Apr. 1979.

Funt, B. V., and Bryant, E. C., Detection of Internal Log Defects by Automatic Interpretation of Computer Tomography Images. Forest Prod. J. 37(1): 56-62, 1987.

Galligan, W. C., and Courteau, R. W., Measurement of Elasticity of Lumber With Longitudinal Stress Waves and the Piezoelectric Effect of Wood, Proceedings of the Second Symposium on the Nondestructive Testing of Wood. Washington State University, Pullman, WA. 1965.

Gerhards, C. C., Effect of Cross Grain on Stress Waves in Lumber, Forest Products Laboratory Research Paper FPL 386, U.S. Department of Agriculture, Forest Service, Madison, WI, May 1980.

Groom, L., and Polensek, A., Nondestructive Prediction of Load-Deflection Relations for Lumber, Wood Fiber Sci. 19(3): 298-312, 1987.

Godinez, P. A., Automated Optical Inspection of Wood Grain Patterns and Defects, Proceedings 2nd International Conference on Scanning Technology in Sawmilling, Oakland/Berkeley Hills, CA, XVI-1-XVI-5, Oct . 1987.

Hailey, J. R. T., and Swanson, J. S., Imaging Wood Using Magnetic Resonance, Proceedings 2nd International Conference on Scanning Technology in Sawmilling, Oakland/Berkeley Hills, CA, VII–1–VII–12. Oct. 1987.

Hoyle, R. J., Background to Machine Stress Rating, Forest Prod. J. 18(4):87-97, 1968.

Hoyle, R. J., and Pellerin, R. F., Stress Wave Inspection of a Wood Structure, Proceedings of the Fourth Nondestructive Testing of Wood Symposium, Washington State University, Pullman. WA, 1978.

James, W. L., Boone, R. S., and Galligan, W. L., Using Speed of Sound to Monitor Drying in a Kiln, Forest Prod. J. 32(9): 27–34. 1982.

James, W. L., Yen, Y., and King, R. J., A Microwave Method for Measuring Moisture Content, Density, and Grain Angle of Wood, Forest Products Laboratory Research Note FPL-0250, U.S. Department of Agriculture, Forest Service, Madison, WI, 1985.

Jayne, B. A., Vibrational Properties of Wood as Indices of Quality. Forest Prod. J. 9(11): 413–416, 1959.

Jung, J., Stress–Wave Grading Techniques on Veneer Sheets, Forest Products Laboratory Research Paper FPL 27, U.S. Department of Agriculture, Forest Service, Madison, WI, 1979.

Kaiserlik, J. H., and Pellerin, R. F., Stress Wave Attenuation as an Indicator of Lumber Strength. Forest Prod. J. 27(6) : 39–43. 1977.

Lanius, R. M., Tichy, R., and Bulleit, W. M., Strength of Old Wood Joists, J. Struct. Div. ASCE 107(ST12), 1981.

Lemaster, R. L., and Dornfeld, D. A., Preliminary Investigation of the Feasibility of Using Acousto–Ultrasonics to Measure Defects in Lumber, J. Acoust. Emiss. 6(3): 157–165, 1987

Logan, J. D., Machine Stress Rating. Proceedings of the Fourth Nondestructive Testing of Wood Symposium. Washington State University, Pullman, WA. 1978.

McDonald, K. A., Lumber Defect Detection by Ultrasonics, Forest Products Laboratory Research Paper FPL 311, U.S. Department of Agriculture, Forest Service, Madison, WI, 1978.

McDonald, K. A., and Bendtsen. B. A.. Localized Slope–of–Grain––Its Importance and Measurement, Proceedings of the Fifth Nondestructive Testing of Wood Symposium, Washington State University, Pullman, WA. pp. 477–489, 1985.

McDonald, K. A., and Cox, R. G., Ultrasonic Detection of Lumber Defects, U.S. Patent No. 3,664,180, 1972.

Miller, E. D., Taylor. F. L., and Popeck, R. A., A Sonic Method for Detecting Decay in Wood Poles, American Wood Preserves Association, Form No. 1351, 1965.

Murphy, M. W., Franklin D. E., and Palylyk, R. A., A Nondestructive Testing Technique for Wood Poles, B.C. Hydro Research and Development, Surrey, BC, 1987.

Patton–Mallory, M., Anderson, K. D, and DeGroot, R. C.. An Acousto–Ultrasonic Method for Evaluating Decayed Wood, Proceedings of Sixth Nondestructive Testing of Wood Symposium, Washington State University, Pullman, WA, pp. 167-189, 1987.

Pellerin, R. F., Vibrational Approach to Nondestructive Testing of Structural Lumber, Forest Prod. J. 15(3): 93-101, 1965.

Pellerin, R. F., Nondestructive Testing of Wood––A Possible Method for Timber Piling, Proceedings of the Fourth Nondestructive Testing of Wood Symposium, Washington State University, Pullman, WA, 1978.

Porter, A. W., E1-Osta, M. L., and Kusec, D. J., Prediction of Failure of Finger Joints Using Acoustic Emissions, Forest Prod. J. 22(9): 74-82, 1972.

Ross, R. J., and Pellerin. R. F., NDE of Wood–Based Composites With Longitudinal Stress Waves, Forest Prod. J. 38(5): 39-45, 1988.

Rutherford, P. S.. Nondestructive Stress Wave Measurement of Incipient Decay in Douglas Fir, M.S. Thesis, Department of Civil and Environmental Engineering, Washington State University, Pullman, WA. 1987.

Shaw, D. A., Bandpass Filter Comparator for Confirming the Absence of Serious Internal Voids in Wood Poles, IEEE Trans. Instrum. Meas. IM–27 (31), 1978.

Soest, J. F., Applications of Optical Measurements of Slope of Grain, Proceedings 2nd International Conference on Scanning Technology in Sawmilling, Oakland/Berkeley Hills, CA, XII–1–XII–10, Oct. 1987.

Vogt. J. J., Evaluation of the Tensile and Flexural Properties and Internal Bond of Medium Density Fiberboard Using Stress Wave Speed and Attenuation, M.S. Thesis, Washington State University, Pullman, WA, 1985.

Walden, C. C., and Trussell, P. C., Sonic Inspection of Marine Piles. Wood Pres. News, Jan. 1963.

Wallis, H., Defect Detection for Wood Classification, Proceedings 2nd International Conference on Scanning Technology in Sawmilling, Oakland/Berkeley Hills, CA. XVIII-1-XVIII-8, Oct. 1987

Wang, S., Suchsland, O., and Hart, J. H., Dynamic Test for Evaluating Decay in Wood. Forest Prod. J. 30(7): 35-37, 1980.

Monitoraggio strutturale dinamico con fibre ottiche

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SOMMARIO

In una struttura, la misura delle variazioni nel tempo delle caratteristiche, sia della risposta statica, sia della risposta dinamica, può altrettanto validamente essere utilizzata in sistemi di monitoraggio per il rilevamento di stati di danno. I sensori in fibra ottica, impiegati da vari anni per la il monitoraggio strutturale, hanno dimostrato ottime caratteristiche di sensibilità e stabilità delle misure nel tempo, come pure di durata di vita.

ABSTRACT

The measurement of the time evolution of the characteristics of the static and dynamic response of a structure can be used to detect damage states in structures. Fibre optic sensing systems have been used for several years for structural monitoring, demonstrating excellent characteristics in terms of sensitivity, stability and durability

1. Introduzione

La sicurezza delle opere del genio civile richiede un controllo periodico delle infrastrutture. I metodi attualmente utilizzati, quali le ispezioni visive o le misure per triangolazione sono spesso complicati nella messa in opera e richiedono la presenza di uno o più operatori specializzati. La complessità ed i costi che ne risultano sono tali da limitare la frequenza delle misure. La risoluzione spaziale è in generale ridotta e solo la presenza di gravi anomalie nel comportamento globale incita a proseguire l'analisi con maggiore dettaglio e precisione.
Esiste dunque un bisogno reale, su scala internazionale, di strumenti che permettano la sorveglianza automatica e permanente all'interno delle strutture stesse, fornendo risultati di grande precisione e buona risoluzione spaziale.
In quest'ottica, il concetto di struttura intelligente (dall'inglese smart structure) ha già provato la sua efficacia in diversi campi dell'ingegneria, in particolare in aeronautica e nello studio dei materiali compositi. Queste strutture sono provviste di una rete interna di sensori a fibre ottiche che permettono la sorveglianza di diversi parametri, critici per la sicurezza ed utili per una pianificazione efficace degli interventi di manutenzione. Si pensi in particolare alle deformazioni, temperature, pressioni, penetrazioni di agenti chimici nocivi, ecc.
I sensori a fibre ottiche presentano dei vantaggi importanti rispetto ai metodi di misura più convenzionali. Tra questi citiamo il loro basso costo, la vasta gamma di parametri misurabili, l'insensibilità ai campi elettromagnetici (linee ad alta tensione, treni, temporali) ed alla corrosione, le loro dimensioni ridotte, la loro flessibilità d'impiego e la grande densità d'informazione che possono fornire.

2. Sensori a Fibra Ottica

Esiste una grande varietà di sensori a fibra ottica adatti al monitoraggio strutturale. Questi sensori sono stati sviluppati negli ultimi 20 anni in ambito accademico ed industriale. Diversamente da quanto avviene negli Stati Uniti dove l'attenzione é rivolta principalmente ai sensori di deformazione locali, in Europa si assiste ad una maggiore diversificazione delle tecniche utilizzate e dei campi d'applicazione. In questo panoramica ci concentreremo sulle tipologie di sensori disponibili su scala industriale o almeno con test avanzati in campo.

La seguente tabella riassume le principali tecnologie di sensori a fibre ottiche che verranno discusse nei prossimi capitoli:

	Parametri misurati	**Aziende e istituti attivi (selezione)**
SOFO	Spostamento, deformazione, inclinazione	SMARTEC, IMAC-EPFL (Svizzera)
Microbending	Spostamento	Osmos (Francia)
Bragg gratings	Deformazione, spostamento, temperatura, pressione	SMARTEC (Svizzera) Micron Optics (USA) FOS&S (Belgio) AOS (Germania) LETI (Francia) EMPA (Svizzera) CiDRA (USA) Blue Road Research (USA) E molti altri…
Fabry-Perot	Deformazione, temperatura, pressione	Fiso, Rocktest (Canada) Luna Innovations (USA) BAM (Germania)
Raman	Temperatura distribuita	SENSA/Schlumberger (UK/USA) Sumitomo (Giappone)
Brillouin	Temperatura e deformazione distribuite	Omnisens, MET-EPFL, SMARTEC (Svizzera) ANDO (Giappone)

3. Il Sistema SOFO®

Il sistema di monitoraggio SOFO® (acronimo francese di Surveillance d'Ouvrages par Fibres Optiques – Monitoraggio Strutturale per mezzo di Fibre Ottiche) si basa sul principio fisico dell'interferometria a bassa coerenza applicata a sensori a fibre ottiche. Lo schema di funzionamento del sistema SOFO® é rappresentato in Figura 1.

Le componenti del sistema sono i sensori a fibre ottiche, l'unità di lettura ed il software di programmazione, acquisizione ed analisi delle misure. Ciascun sensore è formato da due fibre ottiche, una di misura ed una di riferimento, entrambe preservate all'interno di un tubo di protezione in materiale plastico. La fibra di misura é tesa, risultando perciò solidale alla struttura in modo da seguirne le deformazioni.
Al fine di poter rilevare deformazioni in estensione ma anche in contrazione della struttura la fibra di misura é pretesa allo 0.5% della sua lunghezza. La fibra di riferimento é invece lasca, perciò libera ed indipendente dalle deformazioni della struttura. Questa fibra ha lo scopo di auto-compensare gli effetti termici sulle misure fornite dal sensore. Il segnale ottico viene emesso dall'unità di lettura tramite un LED a infrarossi, sdoppiato nelle due fibre all'interno del sensore e quindi riflesso da due specchi (ottenuti per trattamento chimico) posti all'estremità di ciascuna fibra, per ritornare poi all'unità di lettura dove viene demodulato.
Il segnale di ritorno, contenente le informazioni sulle deformazioni che hanno interessato la struttura, viene debitamente trattato e decodificato dall'unità di lettura, per essere quindi visualizzato in forma tabellare e grafica su di un PC grazie al software dedicato SOFO SDB.
La base di misura del sensore standard è compresa tra 25 cm e 10 m con una risoluzione di 2 μm (2/1000 di mm) e una precisione dello 0,2% della deformazione apprezzata. L'intervallo dinamico di misura va da -0.5% in contrazione a +1.0% in estensione.
Il sistema SOFO® é stato sviluppato nei primi anni '90 e dal 1995 é commercializzato ed impiegato per il monitoraggio di svariate infrastrutture civili, di opere del patrimonio storico artistico e nel settore industriale (ponti, dighe, gallerie, edifici storici e residenziali, macchinari industriali, etc.). Il sistema SOFO® é insensibile ai cambiamenti di temperatura, ai campi elettromagnetici, all'umidità e alla corrosione e a tutt'oggi non presenta alcuna deriva o instabilità nelle misure fornite. Il sistema é ideale per monitoraggi a breve e/o a lungo termine. I sensori non necessitano alcuna calibrazione ed inoltre possono essere annegati nel getto di calcestruzzo oppure installati in superficie grazie ad appositi supporti. La notevole lunghezza che la parte attiva di misura dei sensori SOFO® può avere, ne fa un prodotto unico nella famiglia dei sensori a fibra ottica.
Affidabile e più accurato dei sensori tradizionali, il sistema SOFO® può inoltre contare su una misura di deformazione mediata lungo tutta la parte attiva del sensore, offrendo perciò un monitoraggio strutturale globale e non puntuale della struttura, senza quindi influenze dirette da parte di fenomeni locali, quali fessure, zone disomogenee, eccetera.

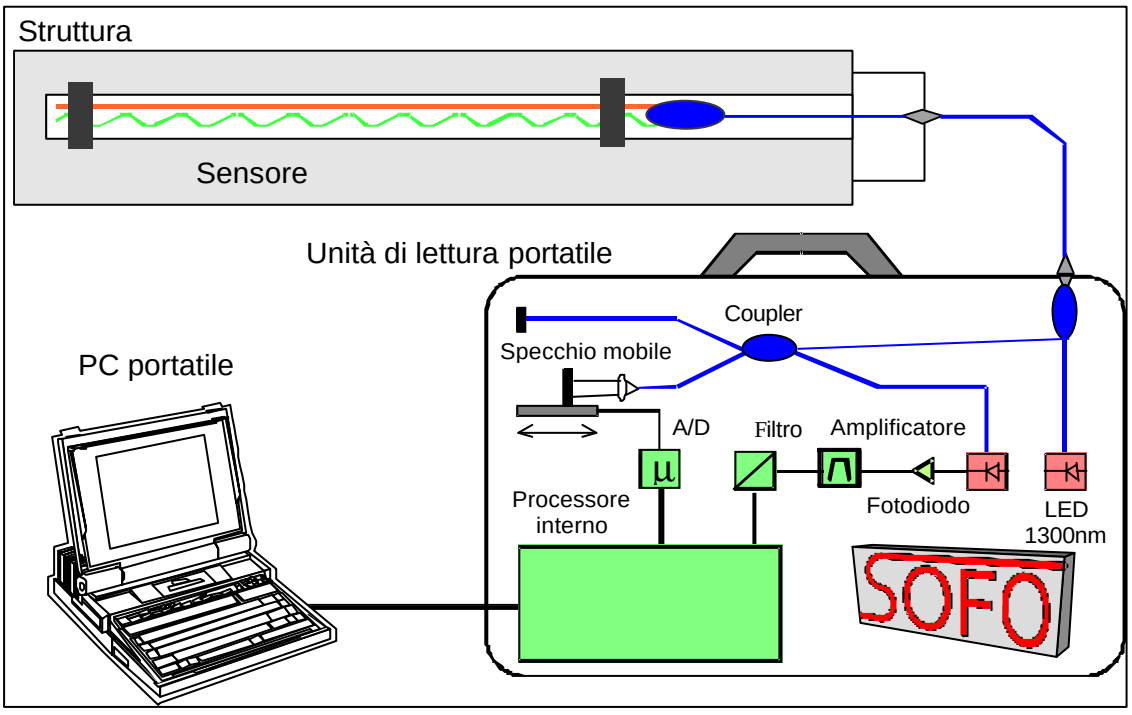

Figura 1: Componenti e funzionamento del Sistema SOFO

Il sistema SOFO® Dinamico

L'unità di lettura SOFO® Dinamico consente la lettura dei sensori SOFO® ad alta frequenza. Ogni unità di lettura può essere utilizzata per acquisire sino ad 8 sensori SOFO® in simultanea. Qualora fosse necessaria la lettura di più sensori, è possibile integrare più unità con funzionamento in parallelo.
L'unità SOFO® Dinamico fa uso di sensori SOFO® Standard compatibili i quali garantiscono le acquisizioni anche con l'unità SOFO V, per misure statiche nel lungo periodo. La maggior parte dei sensori SOFO® standard già installati possono essere acquisiti anche con la nuova unità SOFO® Dinamico, grazie all'utilizzo di un compensatore esterno appositamente concepito.
L'unità di lettura SOFO® Dinamico basa il suo funzionamento sul principio dell'interferometria eterodina a bassa coerenza. Il segnale ottico lanciato da un laser a 1550 nm è modulato in fase mediante un interferometro demodulatore. Acquisito il segnale di ritorno, l'unità di lettura traccia la modulazione di fase introdotta dai sensori e converte lo sfasamento registrato in uno spostamento. La deformazione che ne deriva è trasferibile in formato analogico attraverso gli 8 canali disponibili, oppure in formato digitale attraverso la porta USB, utile per il trasferimento diretto delle acquisizioni ad un PC (salvataggio e conseguente trattamento del segnale).
Lo schema di funzionamento ed i componenti del sistema sono illustrati in Figura 2.
Le misure sono relative, intendendo con questo che lo zero di riferimento è perso ogni qualvolta si interrompe l'acquisizione. Tuttavia, con l'utilizzo complementare dell'unità di lettura SOFO statica, è possibile legare le diverse campagne di misurazione senza perdere il riferimento allo zero iniziale della prima lettura. L'utilizzo combinato del sistema statico permette inoltre l'ottenimento di un quadro completo delle reali condizioni della struttura investigata. La Tabella 1 mette a confronto le caratteristiche del sistema SOFO® nelle versioni statica e dinamica. Come si può osservare, le caratteristiche del sistema dinamico sono addirittura migliori di quelle del sistema statico, anche se le misure (relativa auto referenziata quella del sistema statico e relativa incrementale quella del sistema dinamico) sono di tipo profondamente diverso.

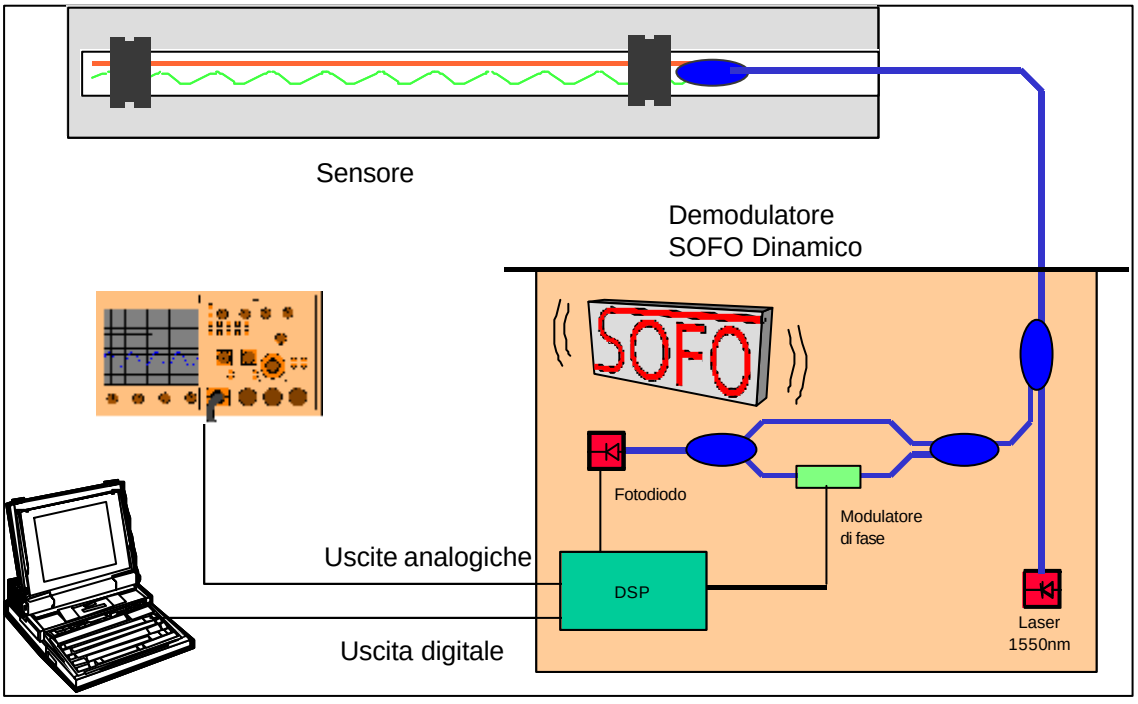

Figura 2: Schema delle componenti del sistema SOFO Dinamico

	Sistema SOFO V Statico	**Sistema SOFO Dinamico**
Campi di applicazione	Monitoraggio statico in quasi real-time nel breve e lungo periodo	Misure dinamiche in real-time nel breve periodo
Tipo di misura	Relativa auto referenziata	Relativa incrementale
Compatibilità dei sensori	Compatibile con tutti i sensori SOFO®	Compatibile con tutti i sensori SOFO®
Range di misurazione	Max 50 mm, funzione della lunghezza del sensore	± 5 mm
Risoluzione	2 μm	0,01 μm
Linearità	< 0,2 % della misura	< 0,2 % della misura
Deriva delle misure	Al di sotto della risoluzione di misura	< 0,003 μm/s, dopo un ora di accensione < 0,5 μm/giorno, usando la compensazione della deriva
Frequenze di acquisizione	Tempo di acquisizione di circa 7 secondi	Da 0 (acquisizione continua) a 1 kHz (10 kHz con configurazione speciale)
Uscite	Database SDB	8 analogiche (20 bits) Digitale: USB 2.0 (32 bits)
Numero di canali	Teoricamente illimitato	8 per unità
Acquisizioni	Sequenziale	Simultanea
Registrazione dati	Data logger integrato	Attraverso dispositivi esterni o tramite PC di controllo

TABELLA 1 – CONFRONTO FRA I SISTEMI SOFO® STATICO E DINAMICO

4. Sensori Microbending

Un altro sistema utilizzato per la misura di deformazione su base di misura lunga é basato sul principio del microbending. In questa configurazione, una fibra ottica multimodale é attorcigliata ad una seconda fibra o ad un filo metallico. Quando questo “doppino ottico” viene allungato, si riscontra un aumento delle perdite di luce trasmessa, causate dalle curvature introdotte vicendevolmente tra le fibre. Misurando l’intensità della luce trasmessa é dunque possibile risalire alla deformazione della struttura sulla quale é montato il sensore.
Tipicamente é possibile ottenere una risoluzione dell’ordine della decina di micron per corti periodi e di 100 μm nel lungo periodo. Questo tipo di sensori é concettualmente semplice, ma presenta delle difficoltà di realizzazione notevoli, in particolare per quanto concerne la calibrazione, la compensazione degli effetti termici e delle derive di intensità a lungo termine. Questi sensori sono dunque più adatti per applicazioni dinamiche e a corto termine, come pure per la realizzazione di sistemi di allarme.

5. Reticoli di Bragg

I reticoli di Bragg basano il funzionamento sulle alterazioni periodiche nell'indice di rifrazione nel cuore della fibra ottica che può essere ottenuta esponendo la fibra ad una adeguata intensità di radiazione UV. I reticoli utilizzati hanno tipicamente una lunghezza di misura dell'ordine di 10 millimetri. Se della luce bianca viene iniettata nella fibra che contiene un reticolo, la lunghezza d'onda che corrisponde al passo del reticolo verrà riflessa, mentre tutte le altre lunghezze d'onda attraverseranno il reticolo indisturbate. Visto che il periodo dei reticoli dipende dall’allungamento della fibra e dalla sua temperatura, é possibile misurare questi due parametri analizzando lo spettro della luce riflessa. Ciò avviene di solito utilizzando un filtro accordabile (quale una cavità di Fabry-Perot) o uno spettrometro. Con i

migliori demodulatori si possono ottenere delle risoluzioni dell'ordine 1 με e 0,1 °C. Se le variazioni di temperatura e le deformazione avvengono simultaneamente, è necessario utilizzare un reticolo di riferimento libero che misuri la temperatura, e utilizzare questa misura per correggere quella ottenuta dei reticoli accoppati meccanicamente alla struttura. L'interesse principale nel uso dei reticoli di Bragg risiede nel loro potenziale di funzionamento in multiplexing. Molti reticoli possono infatti essere scritti nella stessa fibra in posizioni differenti ed essere impostati per riflettere alle lunghezze d'onda diverse. Ciò permette la misura in punti diversi lungo una fibra, pur usando un singolo cavo. Si possono tipicamente misurare tra 4 e 25 reticoli su una singola linea della fibra. Dato che i reticoli devono spartirsi lo spettro della sorgente luminosa usata per illuminarle, il numero dei reticoli e la loro gamma di misura sono tra loro concorrenti ed é perciò necessario trovare un adeguato compromesso per le specifiche applicazioni.

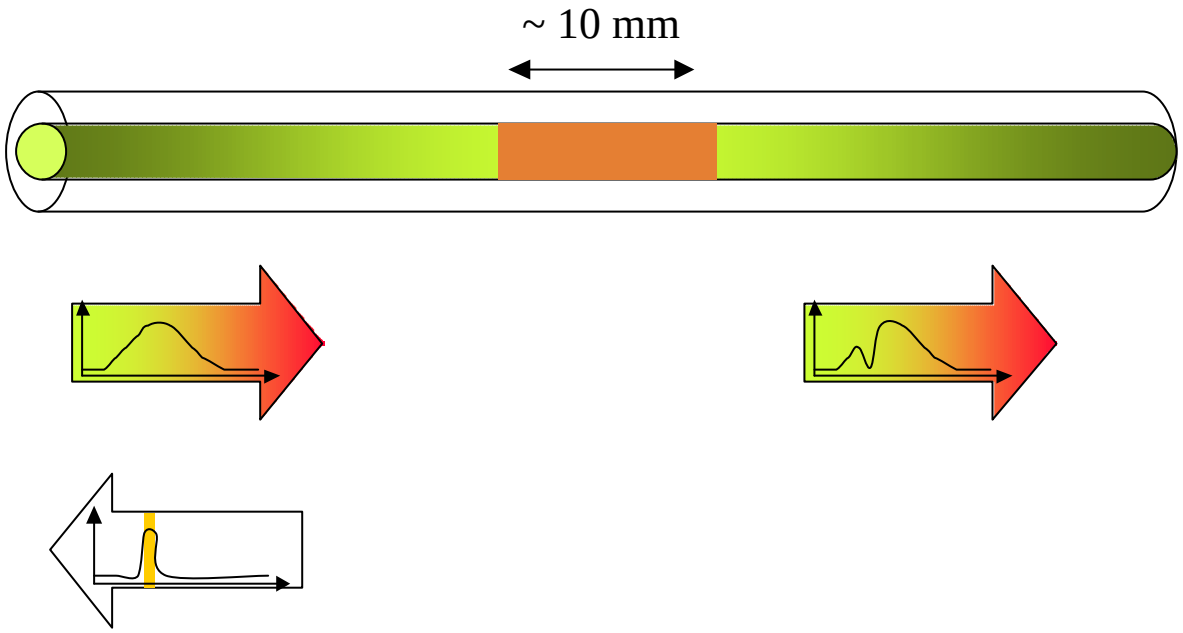

Figura 3: Principio di misura dei sensori a reticoli di Bragg

Per la loro lunghezza, i reticoli di Bragg possono essere utilizzati come equivalenti ottici degli estensimetri convenzionali ed essere installati incollandoli su metalli ed altre superfici regolari. Attraverso un appropriato imballaggio possono anche essere usati per misurare gli sforzi nel calcestruzzo con base di misura tra 10 cm e 2 m.

6. Sensori di Fabry Perot

Gli interferometri di Fabry-Perot (EFPIs: Extrinsic Fabry Perot Interferometer) sono costituiti da un tubo capillare di vetro che contiene due fibre ottiche accuratamente tagliate che si fronteggiano lasciando una piccola fenditura tra le due dell'ordine di alcuni micron o decine di micron. Quando la luce è lanciata in una delle fibre, si ottiene un segnale retro - riflesso di interferenza. Ciò è dovuto alla riflessione della luce all'interfaccia vetro - aria e aria - vetro.

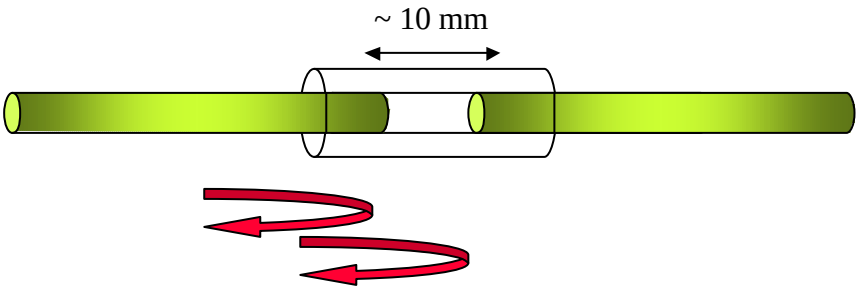

Figura 4: Principio di misura dei sensori di Fabry Perot

Questa interferenza può essere demodulata con tecniche di interferometria coerente o in bassa coerenza per ricostruire le variazioni di distanza tra le fibre. Se le due fibre sono fissate al tubo capillare vicino alle sue estremità, il cambiamento di distanza tra le fibre corrisponderà alla variazione media di tensione fra i due punti di collegamento. Questi sensori costituiscono un'alternativa ai reticoli di Bragg, ma non consentono di installare più sensori lungo la stessa linea.

5. Diffusione Raman

La diffusione Raman è il risultato di un'interazione non lineare fra la luce che si propaga nella fibra ottica e la fibra stessa. Quando un segnale intenso è introdotto nella fibra, si generano due nuove componenti con lunghezze d'onda maggiori e minori del segnale originale.
L'intensità relativa di questi due componenti dipende dalla temperatura locale della fibra. Se il segnale luminoso è pulsato e l'intensità retro-riflessa è registrata in funzione del tempo di volo, diventa possibile ottenere un profilo termico lungo la fibra. Usando delle fibre ottiche multimodali, si può tipicamente ottenere una risoluzione in temperatura dell'ordine di 0.1°C e una risoluzione spaziale dell'ordine di 1m su distanze fino a circa 10 chilometri. Un nuovo sistema basato sull'uso delle fibre monomodali potrebbe estendere la gamma fino a circa 30km con una risoluzione spaziale di 8 m e una risoluzione in temperatura di 2°C.

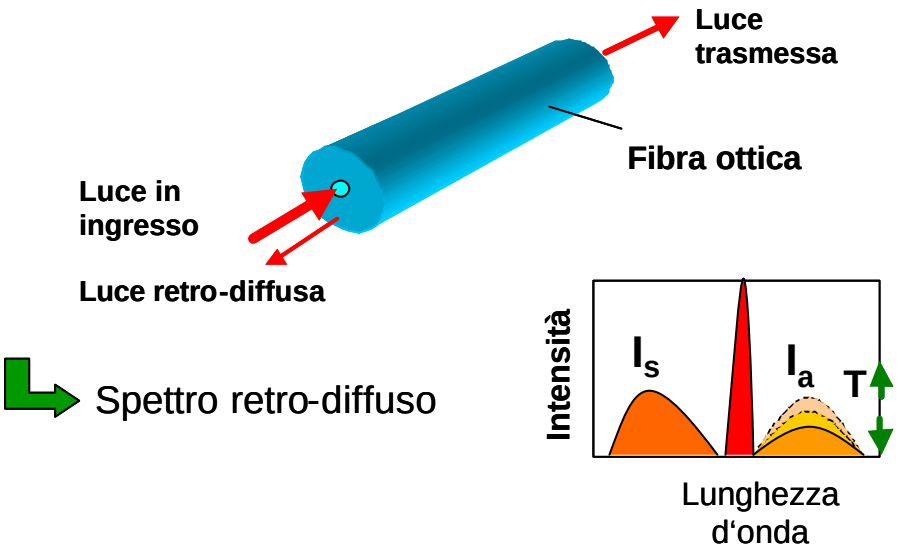

Figura 5: Principio di misura dei sensori distribuiti a diffusione Raman

6. Diffusione Brillouin

L'utilizzo della diffusione Brillouin presenta un interessante potenziale per il controllo distribuito della temperatura e delle deformazioni. Questi sistemi sono in grado di misurare le variazioni locali di questi parametri su distanze fino a 30-50 km con una risoluzione spaziale dell'ordine del metro in condizioni d'uso non di laboratorio. Per le misure di temperatura, i sensori Brillouin sono un temibile concorrente ai sistemi basati sulla diffusione Raman, mentre per le misure di deformazione non hanno praticamente rivali. La Brillouin è il risultato dell'interazione fra le onde acustiche e ottiche che si propagano nella fibra. Le onde acustiche termicamente eccitate (fononi) producono una modulazione periodica dell'indice di rifrazione. La dispersione Brillouin ha luogo quando la luce che si propaga nella fibra viene diffratta all'indietro da questo reticolo in movimento, generando una componente spostata in frequenza (un fenomeno simile allo spostamento di Doppler). Questo processo è denominato

dispersione Brillouin spontanea. Le onde acustiche possono anche essere generate iniettando alle due estremità opposte della fibra due fasci di luce con una differenza di frequenza uguale allo spostamento di Brillouin. Tramite un fenomeno di elettrostrizione, queste due onde provocano un'onda acustica mobile che rinforza la popolazione di fononi. Questo processo è denominato diffusione Brillouin stimolata. Se il segnale della sonda è costituito in un impulso luminoso corto e l'intensità riflessa è rilevata in funzione dello spostamento di frequenza e del tempo di volo, é possibile ottenere un profilo dello spostamento di Brillouin su tutta la lunghezza della fibra.
La caratteristica più interessante della diffusione Brillouin risiede nella dipendenza dello spostamento in frequenza dallo stato di tensione e dalla temperatura locale della fibra ottica. Questo è il risultato del cambiamento della velocità acustica in funzione delle variazione nella densità del vetro. La misura dello spostamento Brillouin può avvenire utilizzando sia la dispersione spontanea, sia quella stimolata. La sfida principale nell'uso della diffusione Brillouin spontanea per applicazioni nel campo del monitoraggio risiede nel livello estremamente basso del segnale rilevato. Ciò richiede un'elaborazione sofisticata dei segnali e tempi di integrazione relativamente lunghi.

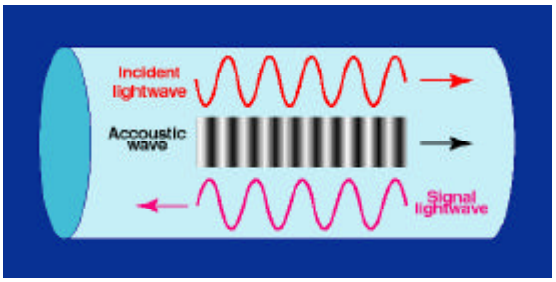

Figura 6: Principio di misura dei sensori distribuiti a diffusione Brillouin

I sistemi basati sulla diffusione Brillouin stimolata presentano il vantaggio di un segnale relativamente più forte, ma presentano per contro un'altra sfida: per produrre un segnale rappresentativo, le due onde in contro-propagazione devono presentare una differenza di frequenza estremamente stabile. Ciò richiede solitamente la sincronizzazione di due laser che devono iniettare i due segnali alle estremità opposte della fibra in esame. Il Politecnico federale di Losanna (laboratorio MET) ha proposto un metodo più elegante basto sulla generazione di entrambe le onde da una singola sorgente laser, usando un modulatore di fase in ottica integrata. Questa disposizione offre il vantaggio di eliminare la necessità di due laser separati, assicurando inoltre che la differenza di frequenza rimanga costante indipendentemente dalle derive del laser.
Omnisens e SMARTEC commercializzano un sistema basato su questo principio chiamato DiTeSt. Questo sistema garantisce una distanza di misura di 10 chilometri con una risoluzione spaziale di 1m o una distanza di 25 chilometri con una risoluzione di 5m. La risoluzione in deformazione é di 20 με e la risoluzione in temperatura è di 1°C. Il sistema è portatile e può essere usato per le applicazioni in campo. Questi valori sono vicino ai limiti teorici per un sistema Brillouin.
Poiché lo spostamento di frequenza della diffusione Brillouin dipende sia dallo stato tensionale locale, sia dalla temperatura della fibra, la concezione del cavo-sensore determinerà il tipo di sensibilità del sistema. Per la misura delle temperature è sufficiente usare un cavo standard per telecomunicazioni. Questi cavi sono appositamente concepiti in modo da proteggere le fibre ottiche in caso di allungamento del cavo. La fibra di misura rimane quindi permanentemente lasca e gli spostamenti di frequenza possono essere assegnati senza ambiguità alle variazioni di temperatura. Se lo spostamento di frequenza della fibra è conosciuto per una data temperatura di riferimento, é possibile calcolare la temperatura assoluta in ogni punto lungo la fibra. La misurazione degli allungamenti distribuiti richiede invece un sensore specialmente progettato che garantisca un

accoppiamento meccanico fra il sensore e la struttura ospite sull'intera lunghezza della fibra. Per risolvere la sensibilità parassita alle variazioni di temperatura, è inoltre necessario installare una fibra di riferimento lungo il sensore di deformazione. Come per il caso della temperatura, la conoscenza dello spostamento in frequenza nella fibra lasca, permette una misura assoluta delle deformazioni.

7. Conclusioni

Il controllo delle strutture nuove ed esistenti è uno degli strumenti essenziali per una gestione intelligente, moderna ed efficiente delle infrastrutture. I sensori sono il primo elemento nella catena di controllo e sono responsabili dell'esattezza e dell'affidabilità dei dati. Il progresso nella tecnologia di rilevamento può quindi tradursi in misure più precise, ma anche in sistemi che sono più facili da installare, usare e gestire. Negli ultimi anni i sensori a fibre ottiche hanno mosso con successo i primi passi nel campo del controllo strutturale ed in particolare nell'ingegneria civile. Diverse tecnologie di misura sono emerse ed alcune sono evolute in prodotti commerciali.
È difficile trovare un elemento comune per motivare il successo dei vari tipi di sensori: ognuno sembra aver trovato una nicchia di mercato dove può offrire delle prestazioni che sorpassano o completano quelle dei sensori più tradizionali. Dovendo scegliere tre caratteristiche dei sensori a fibre ottiche che possano spiegarne il successo presente e futuro, citerei la stabilità delle misure, l'affidabilità nel lungo termine e la possibilità di acquisire misure distribuite e a grande distanza.
Nell'immediato futuro é dunque da prevedere che i sensori a fibre ottiche consolidino la loro presenza nell'industria del monitoraggio strutturale.

Bibliografia

[1] *Glisic B., D. Inaudi, A. Del Grosso, F. Lanata e G. Brunetti,2002, Monitoraggio a breve e a lungo termine delle strutture in calcestruzzo tramite sensori a fibre ottiche, Atti del 22° Convegno Nazionale AICAP, Pàtron Editore, Bologna, pp. 531-540*

[2] "Photonic sensing technology in civil engineering applications", D. Inaudi, Handbook of optical fibre sensing technology, J. M. Lopez-Higuera editor, Wiley'(2002), Wiley.

ISTITUTO PER LA CONSERVAZIONE E LA VALORIZZAZIONE DEI BENI CULTURALI

Consiglio Nazionale delle Ricerche

MONITORING PAINTED FAÇADES AFTER A CONSERVATIVE INTERVENTION

MOMOREX PROJECT

BIBLIOGRAPHICAL SURVEY

STATE-OF-THE-ART

Sara Serrão · December 2003

1. STUDY CHARACTERISTICS

The MOMOREX project, aims: using the most useful diagnostic technologies for the identification and specification of the significant criteria for monitoring the state of conservation of painted façades, subsequent to recent restoration; creating a model to check the variations, both as to quantity and as to quality, of deterioration elements within a time unit

The bibliographical survey, aims: state-of-the-art of monitoring façades after a conservative intervention, in order to verify the novelty of its concept and the actuality of the analysis methods proposed

Duration of the survey: 2 months (9 October - 16 December 2003)

Methodology:

1) General research on wall painting monitoring and on the analysis techniques for specific parameters: internet (**bcin**: www.bcin.ca, **aata**: http://aata.getty.edu, **iris**: http://ps610.iris.firenze.it/ALEPH) and local library (at ICBCV)
2) Elaboration of a table for bibliographical data, with the following characteristics:
- selection of matters regarding monitoring or the analysis of specific parameters + bibliographical references
- direct correlation with MOMOREX project: selection of the nature of parameters and systematisation of the information according to them (chromatic-aesthetical, physical, chemical, biological and surrounding environment)
- being useful for further investigation
- being easy to consult by any person interested in the methods referred
3) Consultation of the selected publications
4) Evaluation of the tables obtained and further investigation on missing subjects (considering the different parameters)
5) Interpretation of all the information and conclusions on the state-of-art of façades monitoring

Final documents: tables summarizing the following information

- Publications consulted (see *Annex 1*)
- Methods for the analysis of specific parameters (see *5. Methods for analysing the specific parameters*)

Number of articles consulted: 59

2. GENERAL CONCLUSIONS

- No studies have been found which include a complete monitoring (i.e. to various significant degradation parameters) on a painted façade, nor the monitoring of a painted façade after a conservative and restorative intervention – therefore the MOMOREX project is a novelty as conservation methodology;
- Little study has been developed concerning the diagnosis and monitoring of painted walls in external environment: only two studies have been found considering environmental monitoring of wall paintings placed outside, namely "America Tropical", a painting by the Mexican artist David Alfaro Siqueiros in Los Angeles, and a medieval painting in S. Scolastica's Monastery in Subiaca (Rome, Italy). "America Tropical" was monitored during over one year and a half (starting 1994) for wind speed and direction, rainfall, temperature, humidity and the movement of sunlight across the mural's surface, before the application of a shelter [35]; details on the monitoring system aren't mentioned. On the other hand, the front fresco of the gothic church in S. Scolastica was monitored for the hygrothermic parameters plus superficial temperature (in two campaigns between 1989 and 1992), in order to study it's deterioration phenomena and, lately, to check the effectiveness of closing its surrounding area and to control dangerous condensation periods [29]; the monitoring instruments aren't specified. One other study considers the diagnosis of painted façades, in order to comprehend degradation processes due to air pollution, namely at the external frescoes in Padova (determination of the pollutants composition and concentration using X-ray fluorescence, X-ray diffraction and IR spectroscopy [13]). These data reveal that the study of painted façades is still in an early stage and should be developed, in order to promote the application of specific and adequate methodologies for the conservation of mural paintings exposed to outside environment;
- A couple of studies mention the analysis of wall paintings after its restoration, in order to assess its effectiveness, and both study cases are located in internal environment: Cappella Brancacci, Florence (chromatic parameters [17]), Fogolino's fresco in Malpaga Castle, Bergamo, Italy (thermal diffusion [15]) – monitoring the effectiveness of treatments effectuated on painted façades shall be a novelty;
- Considering that little study has been effectuated on monitoring painted façades, the state-of-the-art of the methodologies available shall extravasate this specific type of analysis and include, as well, those techniques applied for similar purposes. In the present study we've considered:
    - methods for monitoring wall paintings in internal environment;
    - methods for monitoring monuments in external environment;
    - methods used for the analysis of the degradation parameters selected within the MOMOREX project.

  Thus, the present survey permits to evaluate the actuality of the methods proposed.

3. MONITORING OF WALL PAINTINGS IN INTERNAL ENVIRONMENT

- Wall paintings in internal environment are often monitored, e.g. paintings of Horsham St Faith priory, Norfolk, England (surrounding environment monitoring [33]); Tomb of Queen Nefertari, Thebes, Egypt (chromatic patterns [52; 54] and surrounding environment monitoring [40]); Cappella Sistina, Vatican (pollutants [9] and micro organisms monitoring [43]);
- Some are monitored previously to their intervention, with a diagnostic purpose: Brancacci Chapel, Florence, Italy (chromatic-aesthetical and physical parameters [17]); Simone Martini's "Maestà", Siena, Italy (chromatic-aesthetical and chemical parameters, surrounding environment [51]);
- Some are analysed before the intervention and monitored for its effectiveness afterwards: Cappella Brancacci, Florence (chromatic parameters [17]), Fogolino's fresco in Malpaga Castle, Bergamo, Italy (thermal diffusion [15]).

4. MONUMENTS IN EXTERNAL ENVIRONMENT

- Monuments in external environment are often monitored, in order to comprehend degradation processes, e.g. the sculpture of Marcus Aurelius in Rome (surface temperature, thermal diffusion and sonic waves [1]), the cupola of Brunelleschi in Florence (fissures, surface temperature and humidity [11], thermal diffusion [23]), the Toledo cathedral in Spain (thermal diffusion [28]), El Escorial in Madrid and Sta. Maria de Ripoll in Gerona, Spain (ultrasonic waves [44]), the church of Saint-Trophime in Arles, France (wind velocity and direction, pollutants composition [34]), Parma cathedral and baptistery in Italy, Lund cathedral in Sweden (micro organisms [45]);
- Some are analysed before the intervention and monitored for its effectiveness afterwards: church of Saint-Trophime in Arles, France [34].

5. METHODS FOR ANALYSING THE SPECIFIC PARAMETERS

Analysis methods were investigated through the bibliographical survey, in order to understand what techniques have been used to determine those parameters considered by the MOMOREX project. The information obtained was systemised in tables and organized according to the nature of the parameters.

Chromatic-aesthetical: surface patterns

Instrument	Type of analysis	Application	Case Study	Publ. year	Bibl.
Photogrammetry; holography; optoelectronic scanning recording	Diagnosis	Wall surfaces	-	1989	[2]a
Photogrammetry	Diagnosis	Wall painting (interior)	Cappella Brancacci, Florence, Italy	1991	[17]
Photogrammetry: Galileo's metric camera Verostat	Diagnosis	Wall painting (interior)	'Maestà' Simone Martini, Palazzo Pubblico, Siena, Italy	1992	[51]
Direct digital capture: Hasselblad camera with a Zeiss lens and Leaf digital camera back + Quadra 950 computer with extended ram and a 20-inch color monitor + special scaffolding that moved on a self-leveling trackway, and a camera dolley that rode on its own track at the top of the scaffolding [equipment designed by Eric Lange]	Documentation and monitoring	Wall painting (exterior)	David Siqueiros "America Tropical", Los Angeles, USA	1994	[35]
Photogrammetry	Documentation	Historical building	Timurid Monuments, Samarkand, Uzbekistan	2000	[19]
Remote sensing : laser scanning (+ digital photogrammetry)	Diagnosis and monitoring	Historical building	-	2000	[20]

Instrument proposed within the MOMOREX program: digital standard & raking light images, macro photos + GIS

Chromatic-aesthetical: chromatic coordinates

Instrument	Type of analysis	Application	Case Study	Publ. year	Bibl.
Colourmeter "Santini"; colourmeter laser	Diagnosis	Wall surfaces	-	1989	[2]b
Minolta CR-121 ChromaMeter with a DP-100 data processor	Monitoring	Wall painting (interior)	Tomb of Queen Nefertari, Egypt	1991	[52]
Minolta Chroma Meter CR-121	Monitoring	Wall painting (interior)	Tomb of Nefertari, Egypt	1993	[54]
Brilliance values: spectrophotometric colourmeter Minolta CM-2002, image analysing videomicroscope Simitecno, EIS Electronic Industry Support equipment for automatic measurements (R, G, B values determination + micromaps of different grey levels)	Diagnosis / monitoring	Stone (exterior)	S. Maria Maggiore Basilica and Teatro di Marcello, Rome; Villa d'Este Cloister and Villa Adriana, Tivoli, Italy	1996	[39]

Instrument proposed within the MOMOREX program: colourmeter + GIS

Chromatic-aesthetical: other parameters – colour spectre

Instrument	Type of analysis	Application	Case Study	Publ. year	Bibl.
Spectrophotometric analysis by means of fiber optic	Diagnosis + evolution of treatment	Wall painting (interior)	Cappella Brancacci, Florence, Italy	1991	[17]
Optical fiber reflectance spectroscopy	Diagnosis	Wall painting (interior)	-	1992	[10]
Spectrophotometric colourmeter Minolta CM-2002	Diagnosis / monitoring	Stone (exterior)	S. Maria Maggiore Basilica and Teatro di Marcello, Rome; Villa d'Este Cloister and Villa Adriana, Tivoli, Italy	1996	[39]
Remote sensing : laser spectral scanning (+digital photogrammetry)	Diagnosis and monitoring	Historical building	-	2000	[20]

Instrument proposed within the MOMOREX program: - (program doesn't consider this parameter)

Physical: micro vibration

Instrument	Type of analysis	Application	Case Study	Publ. year	Bibl.
Laser Dopler scanning vibrometer	Diagnosis (project)	Wall painting	-	1999	[56]

Instrument proposed within the MOMOREX program: x-y accelerometer

Physical: fissures

Instrument	Type of analysis	Application	Case Study	Publ. year	Bibl.
Deformometer; system of lead strings and tele-coordinometer; hydraulic levelmeter + piezometer [verificar termos]	Monitoring	Historical building	Cupola of Brunelleschi, Florence, Italy	1992	[11]

Instrument proposed within the MOMOREX program: fissurometer

Physical: surface temperature and humidity

Instrument	Type of analysis	Application	Case Study	Publ. year	Bibl.
T: thermocouples type K Chromel-Allumel; Leeds and Northrup multitrace potentiometric recorder	Diagnosis	Metal (exterior)	Marcus Aurelius, Rome, Italy	1983	[1]
H: Carbide meter	Diagnosis / monitoring	Wall surfaces	-	1991	[6]
H: Electrical resistance meter (ERM) + dielectric constant meter (DCM) + sampling (samples dried to a constant weight in laboratory for a direct measurement of moisture content + exposure to 70% RH at 20ºC in a humidity chamber to determine the hygroscopic absorption)	Monitoring	Wall painting (interior)	Horsham St Faith priory, Norfolk, England	1991	[33]
T: thermocouples **H:** glass bell (which isolates a solid volume with the wall) with a thermohygrometer and a wall thermocouple	Diagnosis	Historical building	Cappella Portinari, S. Eustorgio, Milan, Italy	1992	[57]
T: Electric resistor thermometer	Monitoring	Historic building	Cupola of Brunelleschi, Florence, Italy	1992	[11]

T: Electronic data acquisition system, with sensors for air temperature and humidity + surface temperature	Monitoring	Exterior / interior	Front fresco of the gothic church in S. Scolastica's Monastery in Subiaco, Rome, Italy	1994	[29]
T: Thermometer, radiometer, thermograph	Monitoring	Objects in museum	-	2003	[12]

Instrument proposed within the MOMOREX program: contact thermo hygrometer

Physical: thermal diffusion

Instrument	Type of analysis	Application	Case Study	Publ. year	Bibl.
AGA Thermovision equipment mod.750	Diagnosis	Metal (exterior)	Marcus Aurelius, Rome, Italy	1983	[1]
Thermography, thermovision	Diagnosis	Wall surfaces	-	1989	[2]c
Thermography	Diagnosis	Wall paintings (interior)	Cappella Brancacci, Florence, Italy	1991	[17]
Thermography	Diagnosis	Historical building	Brunelleschi Dome in S. Maria del Fiore, Florence, Italy	1991	[23]
Infrared thermography	Diagnosis/ monitoring	Historical building	Cathedral of Toledo, Spain	1992	[28]
Multispectral optical analysis	Diagnosis	Stone	-	1993	[8]
TNDT Thermal Non Destructive Testing, based on IR thermography	Diagnosis+ evolution of treatment	Wall painting (interior)	Fogolino's fresco in Malpaga Castle, Bergamo, Italy	2000	[15]

Instrument proposed within the MOMOREX program: thermovision

Physical: sonic or ultrasonic waves

Instrument	Type of analysis	Application	Case Study	Publ. year	Bibl.
Acoustic emission equipment: Atel FRIDET	Diagnosis	Metal (exterior)	Marcus Aurelius, Rome, Italy	1983	[1]
Electro-mechanic system	Diagnosis	Wall surfaces	-	1989	[2]d
Ecography with ultrasound	Diagnosis	Wall paintings (interior)	Cappella Brancacci, Florence, Italy	1991	[17]
Pulse velocity measuring equipment	Diagnosis	Stone	-	1991	[41]
Ultrasonic pulse system: "New Sonicviewer" + AE/MS signal processing system: "Spartan 3000"	Monitoring	Stone	El Escorial, Madrid; Sta. Maria de Ripoll, Gerona, Spain	1991	[44]
Vibrational TV-holography combined with acoustical excitation	Diagnosis / monitoring	Wall paintings	Wall paintings in the church of Eilsum, Ostfriesland, Germany	1996	[25]

Instrument proposed within the MOMOREX program: sonic & ultrasonic equipments

Physical: surface micro profiles

Instrument	Type of analysis	Application	Case Study	Publ. year	Bibl.
Double exposure laser holography	Diagnosis	Wall paintings (interior)	Cappella Brancacci, Florence, Italy	1991	[17]
Holographic contouring technique	Diagnosis and monitoring	Stone	Marble head of Roman age, museum of L'Aquila, Abruzzo, Italy	1991	[46]

ESPI: Electronic Speckle Pattern Interferometry	Monitoring	Historic buildings / wall paintings	-	1992	[30]
TV holography = ESPI	Diagnosis	Wall painting	-	1995	[47]
HINDT (Holographic Interferometry Non-Destructive Testing), ESPI (Electronic Speckle Pattern Interferometry), IR imaging system with spectral sensitivity between 1-2.5μm	Diagnosis (project)	Wall painting	-	1999	[56]
Remote sensing: laser scanning	Diagnosis and monitoring	Historical building	-	2000	[20]

Instrument proposed within the MOMOREX program: digital standard images (macro photos + GIS), laser profilometer

Physical: water absorption

Instrument	Type of analysis	Application	Case Study	Publ. year	Bibl.
Drilling a solid core	Diagnosis	Wall surfaces	-	1991	[6]
Permeability box method, pipe method	Diagnosis	Stone	-	1991	[41]

Instrument proposed within the MOMOREX program: contact sponge

Physical: other parameters

Parameter	Instrument	Type of analysis	Application	Case Study	Publ. year	Bibl.
Electric resistance (moisture analysis)	Two electrodes: "Acqua Boy", "Gann Hydromett", "Protimeter"	Diagnosis	Wall surfaces	-	1989	[2]e
Electrical conductivity (moisture analysis)	Two electrodes	Diagnosis / monitoring	Wall surfaces	-	1991	[6]
Ressonance frequency	Longitudinal vibration	Diagnosis	Stone	-	1991	[41]
Porosity	Measurement in a vacuum camera, mercury porosimetry, suction test	Diagnosis	Stone	-	1991	[41]
Porosity	Porosimetry with mercury penetration	Diagnosis	Historic building	Scuola Grande dei Carmine, Venice, Italy	1993	[14]
Porosity	Image analysis; mercury porosity; absorption	Diagnosis	Stone	-	1993	[8]

Instrument proposed within the MOMOREX program: - (program doesn't consider these parameters)

Chemical: chemical / elemental composition and concentration

Instrument	Type of analysis	Application	Case Study	Publ. year	Bibl.
Surface deposits: X-ray fluorescence, X-ray diffraction, IR spectroscopy	Diagnosis	Wall painting (exterior)	External frescoes in Padova, Italy	1990	[13]
Sulphates, nitrates, chlorides: poultice of paper bulb, FRX, ionic chromatography	Diagnosis	Wall painting (interior)	"Maestà" of Simone Martini, Palazzo Pubblico, Siena, Italy	1992	[51]

Chlorides: neutron probe PGNA Prompt Gamma / Neutron Activation	Diagnosis	Historic building	-	1992	[36]
Salts: poultice of paper bulb with water, conductometer, atomic absorption analysis / commercial half-quantitative water test sets from Merck	Diagnosis	Wall painting	Church of St. Georgen, Styria, Austria	1993	[59]
Surface deposits: A.A and C-S analyser, spectro-photometric infra-red analysis, electronic scanning microscope	Diagnosis	Historic building	Scuola Grande dei Carmini, Venice, Italy	1993	[14]
Black crusts: photoionic microscopy on thin-sections and x-ray diffraction, wet chemical analysis, Analytical Scanning Electron Microscopy	Diagnosis / monitoring	Historic building	Church of Saint-Trophime in Arles, France	1993	[34]
Soluble salts: wetted cellulose wadding + conductivity, pH and alkalinity measurement + Liquid Ion Chromatography	Diagnosis	Stone (exterior)	Gotland sandstone sculptures in Sweden	1996	[37]
Material and degradation agents: XRF	Diagnosis / monitoring	-	-	1999	[38]
Sulphur and chlorine compounds: EDXRF	Diagnosis	Wall paintings and stone	Frescoes of the church of S. Stefano Rotondo in Rome, of Piero della Francesca in the church of S. Francesco in Arezzo, of Domenico in the Nolfi chapel, cathedral of Fano, and of the Basilica of S. Clemente in Rome, Italy	2000	[18]
Black crusts: Composition: transversal thin sections observed by optical microscopy, SEM Philips XL20, FT-IR in the mid-infrared, XRD diffractometry Quantity: DTA-TGA gravimetric and differential thermal analysis, ion chromatography, CHNSO elemental analysis by combustion, ICPS inductivily coupled plasma emission spectrometry	Diagnosis	Historical building	Palazzo Rasponi façade in Ravena, Italy	2000	[53]
Original material: EDXRF Energy dispersive X-ray fluorescence spectrometer	Diagnosis	Wall painting	Roman wall painting, 'Criptoportico' of Trajan's Baths, Rome, Italy	2001	[55]

Instrument proposed within the MOMOREX program: portable FT-IR, EIC, XRF, UV-VIS, GC-MS

Biological: microbial markers

Instrument	Type of analysis	Application	Case Study	Publ. year	Bibl.
SEM, TEM + cyctochemistry	Diagnosis	Wall painting (interior)	Domus Aurea, Rome, Italy	1991	[5]
"Rodak contact" method	Diagnosis / monitoring	Wall painting	Cappella Sistina, Vatican	1992	[43]
Sampling with tape, Q-tips or velvet; SEM and fluorescence analysis, UV light; portable glass-fiber CCD-microscope; recommended: application of fluorescent dye Chalcofluor White M2R (CFW) Sigma	Diagnosis	-	-	1992	[49]

Sampling with plaque or velvet, prepared with specific culture grounds for the different micro-organisms	Diagnosis	Wall painting (interior)	"Maestà" of Simone Martini, Palazzo Pubblico, Siena, Italy	1992	[51]
Short wave length (blue) LED technology	Monitoring (project)	Stone and wall surfaces	-	1999	[58]
Laser radar for fluorescence spectrometry: LIF (laser induced fluorescence), FLIDAR (fluorescence lidar), LTH lidar	Diagnosis and monitoring	Stone	FLIDAR: Parma Cathedral and Baptistery, Italy LTH: Lund Cathedral, Sweden	2000	[45]
MAM *Monitoraggio Ambientale Microbico*: air monitoring (sedimentation plaques operated by a Sed-Unit instrument) + surface monitoring (AM *adesione microbica* + AMO *adesione microbica oraria* → nitrocellulose membranes)	Monitoring	Museum (interior)	National Gallery of Umbria in Perugia, Modern Art Museum in Gubbio, Italy	2000	[50]

Instrument proposed within the MOMOREX program: epifluorescence O.M., luminometer – PCR, isolation cultural media

Surrounding environment: temperature and humidity

Instrument	Type of analysis	Application	Case Study	Publ. year	Bibl.
Hair thermohygrometer; thermoresistor sensors, at solid state or thermocouple	Diagnosis	Interior / exterior	-	1989	[2]f
Thermohygrographs + aspirated digital thermohygrometer	Monitoring	Interior	Wall paintings of Horsham St Faith priory, Norfolk, England	1991	[33]
T: Pt 100 Novasina **RH:** Electrolytic sensors Novasina	Diagnosis	Interior	"Maestà" of Simone Martini, Palazzo Pubblico, Siena, Italy	1992	[51]
Electronic data acquisition system, with sensors for air temperature and humidity + surface temperature	Monitoring	Exterior / interior	Front fresco of the gothic church in S. Scolastica's Monastery in Subiaco, Rome, Italy	1994	[29]
H: High resolution electronic psicometer **RH:** capacity sensors	Monitoring	Interior	-	2003	[12]

Instrument proposed within the MOMOREX program: thermohygrometer

Surrounding environment: rain amount on surface

Instrument	Type of analysis	Application	Case Study	Publ. year	Bibl.
ARA – Acid Rain Analyser	Monitoring	Exterior	-	1992	[48]

Instrument proposed within the MOMOREX program: pluviometer

Surrounding environment: sun irradiance

(no article found specifically on this parameter; see table *Surrounding environment: systems*)
Instrument proposed within the MOMOREX program: photosensors

Surrounding environment: wind velocity and direction

Instrument	Type of analysis	Application	Case Study	Publ. year	Bibl.
Anemometer and a vane set on the roof	Diagnosis + evolution of treatment	Exterior	Church of Saint-Trophime in Arles, France	1993	[34]
Hot string anemometer	Monitoring	Interior	-	2003	[12]

Instrument proposed within the MOMOREX program: anemometer

Surrounding environment: composition and concentration of pollutants / particles

Instrument	Type of analysis	Application	Case Study	Publ. year	Bibl.
Suction instrument with a reactive solution for selective absorption of gaseous pollutants + analytical methods; cellulose-based filters for particles; denuders	Diagnosis	Exterior	-	1989	[2]g
Sampling train consisting of two denuders coated with 2% Na_2CO_3 and 1% glycerine in methanol/water 50/50 in series (oxalic acid) separated by a teflon filter Gelman TF 1000 (oxalate) + ion chromatography	Diagnosis / monitoring	Exterior	Monte-rotondo, Italian town	1991	[21]
Denuder and filters of cellulose acetate, ionic chromatograph DIONEX, atomic absorbance spectrophotometer (lead analysis)	Diagnosis / monitoring	Interior	Cappella Sistina, Vatican	1992	[9]
Fog collector and ionic chromatograph (pollutants in fog)	Monitoring	Exterior	-	1992	[24]
Filters of cellulose acetate or Metricel Gelman filters DM/450 (particles); Gelman flame-photometry apparatus + Philips apparatus with a coulormetric unit (SO_2); scavenging towers with diluted solution of sulphuric acid (ammoniac)	Monitoring	Interior	-	1992	[42]
ARA – Acid Rain Analyser: rain-gauge + conductivity, pH and temperature analysers + further analysis	Monitoring	Exterior	-	1992	[48]
UV fluorescence Dasibi 4108 (SO_2); chemiluminescence Dasibi 2108 (NOx); IR Siemens Ultramat 21P (CO_2); Gravimeter TCR Tecora (particles)	Diagnosis	Interior	"Maestà" of Simone Martini, Palazzo Pubblico, Siena, Italy	1992	[51]
Atmospheric gas captor for an automatic and permanent measure of the gas levels in the environs; automatic aperture pluviometers with serial samplings of rain, fog captors and calibrated air filtration membranes for aerosol particles + filtration, Analytical Scanning or Transmission Electron Microscopy and X-ray fluorescence	Monitoring + evolution of treatment	Exterior	Church of Saint-Trophime in Arles, France	1993	[34]
LARA Laser based air pollution monitoring: optical absorption spectroscopy → broadband tunable light sources + high quality photoacoustic detectors	Monitoring (project)	Interior and exterior?	-	1999	[32]
Particles collection with different filters (specific nature and porosity) + analysis: optic or electronic microscopy, x-ray diffraction, IR spectrophotometry, ionic chromatography, thermal and gravimetrical analysis, etc.	Monitoring	Interior	-	2003	[12]
Diffusive samplers: cylindrical glass vial + impregnated disc; set of annular denuders (nitrous and nitric acids)	Monitoring	Interior	Uffizi Gallery, Florence, Italy	2003	[22]

Instrument proposed within the MOMOREX program: particulates samplers, gas trap & samplers, aerobiological samplers

Surrounding environment: systems

Parameter	Instrument	Type of analysis	Application	Case Study	Publ. year	Bibl.
Air temperature and relative humidity, wind speed and direction, sun irradiance, atmospheric pressure	MTX	Diagnosis	Interior	"Maestà" of Simone Martini, Palazzo Pubblico, Siena, Italy	1992	[51]
Air temperature, relative humidity, level of CO_2	Autonomous monitoring station, with the different sensors	Monitoring	Interior / exterior	Tomb of Nefertari, Luxor, Egypt	1993	[40]
Air temperature-humidity + surface temperature + pluviometer + solarimeter	Electronic data acquisition system, with various sensors	Monitoring	Exterior / interior	Front fresco of the gothic church in S. Scolastica's Monastery in Subiaco, Rome, Italy	1994	[29]
Wind speed and direction, rainfall, temperature, humidity and the movement of sunlight across the mural's surface	Environmental monitoring station	Monitoring	Exterior	David Siqueiros' "America Tropical", Los Angels, USA	1994	[35]
Air temperature and relative humidity, on-surface temperature of wall paintings, air velocity, varying illumination according to different areas, outside air temperature and relative humidity, wind speed and direction, rainfalls amount	Data collection system: mainframe computer record of the physical quantities on magnetic tape + specific software for the data treatment in order to monitor the microclimate by appropriate graphics and tables	Diagnosis / monitoring	Interior	Wall paintings in the church of San Clemente, Rome, Italy	1996	[4]

Instrument proposed within the MOMOREX program: MESS Multi Sensor Environmental System?

Surrounding environment: other parameters

Parameter	Instrument	Type of analysis	Application	Case Study	Publ. year	Bibl.
TOW time of wetness	NILU TOW monitor	Monitoring	Interior / exterior	-	1991	[31]

Instrument proposed within the MOMOREX program: - (program doesn't consider these parameters)

6. BIBLIOGRAPHY

[1] ACCARDO Giorgio, CANEVA Claudio, MASSA Sandro (1983): "Stress monitoring by temperature mapping and acoustic emission analysis: a case study of Marcus Aurelius" in *Studies in Conservation,* 28, no. 2, May 1983

[2] ACCARDO Giorgio, VIGLIANO Giuseppina (1989): *Strumenti e materiali del restauro: metodi di analisi, misura e controllo*. Edizioni Kappa

[3] ACCARDO Giorgio, CACACE Carlo, D'ERCOLI Giorgio, GIANI Elisabetta, RINALDI Roberto, SECCARONI Claudio (1992): "Monitoraggio ambientale: analisi e tecniche di intervento strumentale sul territorio" in *3a Conferenza internazionale sulle prove non distruttive, metodi microanalitici e indagini ambientali per lo studio e la conservazione delle opere d'arte: Viterbo 4-9 ottobre 1992.*Istituto Centrale del Restauro | Associazione Italiana Prove non Distruttive Monitoraggio Diagnostica | BetaGamma editrice

[4] ACCARDO G., GERARDI G., RINALDI R.; GIANI E.; SCARDIGLI S. (1996): "Physical methodologies to set up more idoneous environmental conditions for the safety of frescoes: the case of San Clemente in Rome" in *5th International Conference on non-destructive testing, microanalytical methods and environmental evaluation for study and conservation of works of art :art '96*, *September 24-28, Budapest, Hungary* .MKE (Hungarian Chemical Society) | AIPnD (Italian Society for Non-destructive Testing Monitoring and Diagnostics) | ICR (Istituto Centrale per il Restauro)

[5] ALBERTANO P., LUONGO L., GRILLI CAIOLA M. (1991): "Ultrastructural investigations on algal species deteriorating roman frescoes" in *Science, technology, and European cultural heritage: proceedings of the European symposium, Bologna, Italy, 13-16 June 1989.* BAER N.S., SABBIONI C., SORS André I. (ed)

[6] ARENDT Claus (1991): "The Role of the Architectural Fabric in the Preservation of Wall Painting" in *The conservation of wall paintings; proceedings of a symposium organized by the Courtauld Institute of Art and the Getty Conservation Institute, London, July 13-16 1987*. The Getty Conservation Institute. CATHER Sharon (ed)

[7] ARNOLD Andreas, ZEHNDER Konrad (1991): "Monitoring wall paintings affected by soluble salts" in *The conservation of wall paintings; proceedings of a symposium organized by the Courtauld Institute of Art and the Getty Conservation Institute, London, July 13-16 1987*. The Getty Conservation Institute. CATHER Sharon (ed)

[8] ARNOLD A. (1993): "Composition – Mechanical Properties – Porosity and Humidity – Diagnosis of Stony Materials – Pollution effect" in *Congrès International sur la Conservation de la Pierre et autres Matériaux (Actes), Paris, Unesco: 29 Juin – 1er Juillet 1993*. Les Editions Porte Plume. THIEL Marie-Josée (ed)

[9] BACALONI Alessandro, ROTATORI Mauro, FARULLA Antonio (1992): "La caratterizzazione degli inquinanti chimici aerodispersi nella Cappella Sistina" in *3a Conferenza internazionale sulle prove non distruttive, metodi microanalitici e indagini ambientali per lo studio e la conservazione delle opere d'arte: Viterbo 4-9 ottobre 1992.*Istituto Centrale del Restauro | Associazione Italiana Prove non Distruttive Monitoraggio Diagnostica | BetaGamma editrice

[10] BACCI Mauro, BALDINI Francesco, CARLA Roberto, LINARI Roberto, PICOLLO Marcello, RADICATI Bruno (1992): "Colour change analysis of frescoes: an attempt at electronic restoration" in *3a Conferenza internazionale sulle prove non distruttive, metodi microanalitici e indagini ambientali per lo studio e la conservazione delle opere d'arte: Viterbo 4-9 ottobre 1992.* Istituto Centrale del Restauro | Associazione Italiana Prove non Distruttive Monitoraggio Diagnostica | BetaGamma editrice

[11] BARTOLI Gianni, BLASI Carlo, CHIARUGI Andrea, GUSELLA Vittorio (1992): "Il monitoraggio della cupola del Brunelleschi a Firenze" in *3a Conferenza internazionale sulle prove non distruttive, metodi microanalitici e indagini ambientali per lo studio e la conservazione delle opere d'arte: Viterbo 4-9 ottobre 1992.*Istituto Centrale del Restauro | Associazione Italiana Prove non Distruttive Monitoraggio Diagnostica | BetaGamma editrice

[12] BERNARDI Adriana (2003): *Conservare opere d'arte, Il microclima negli ambienti museali*. il prato

[13] BISCONTIN Guido, DRIUSSI Guido, VOLPIN Stefano (1990): "Studio sullo stato di conservazione di affreschi esterni a Padova" in *Le pitture murali*. Firenze: Centro Di | Opificio delle Pietre Dure

[14] BISCONTIN Guido, DRIUSSI G., MARAVELAKI P., ZENDRI E. (1993): "Physical-chemical investigations of stone architectonic surfaces in Venice: the Scuola Grande dei Carmini" in *Conservation of architectural surfaces: stones and wall covering*. Venezia: il Cardo

[15] BISON P.G., BRESSAN C., GRINZATO E., MARINETTI S., MAZZOLDI A. (2000): "Monitoring of fresco restoration by IR thermography" in *Science and Technology for the safeguard of Cultural Heritage in the Mediterranean Basin, Proceedings of the second international congress, 5-9 July 1999 Paris.* Elsevier

[16] BONARRIGO Antonino (1992): "Monitoraggio delle vibrazioni strutturali del timpano superiore della facciata della Basilica di San Marco in Venezia" in *3a Conferenza internazionale sulle prove non distruttive, metodi microanalitici e indagini ambientali per lo studio e la conservazione delle opere d'arte: Viterbo 4-9 ottobre 1992.* Istituto Centrale del Restauro | Associazione Italiana Prove non Distruttive Monitoraggio Diagnostica | BetaGamma editrice

[17] CASAZZA Ornella, GIOVANNONI Sabino (1991): "Preliminary Research for the Conservation of the Brancacci Chapel, Florence" in *The conservation of wall paintings; proceedings of a symposium organized by the Courtauld Institute of Art and the Getty Conservation Institute, London, July 13-16 1987.* The Getty Conservation Institute. CATHER Sharon (ed)

[18] CESAREO R., CAPPIO BORLINO C., STARA G., BRUNETTI A., CASTELLANO A., BUCCOLIERI G., MARABELLI M., TEIXEIRA DE ASSISS J., GIGANTE G.E. (2000): "Analysis of sulphur and chlorine in frescoes and lapideous monuments by using a portable EDXRF apparatus" in *Science and Technology for the Safeguard of Cultural Heritage in the Mediterranean Basin, Proceedings of the second international congress, 5-9 July 1999 Paris*. Elsevier

[19] CESSARI L. (2000): "Preservation, restoration and protection of the Timurid monuments at Samarkand: results of an integrated project" in *Science and Technology for the Safeguard of Cultural Heritage in the Mediterranean Basin, Proceedings of the second international congress, 5-9 July 1999 Paris*. Elsevier

[20] CESSARI L., BACIGALUPO C., Gigliarelli, E. (2000): "Remote sensing methods for detection and diagnosis of the building heritage" in *Science and Technology for the Safeguard of Cultural Heritage in the Mediterranean Basin, Proceedings of the second international congress, 5-9 July 1999 Paris*. Elsevier

[21] DE SANTIS F., ALLEGRINI I. (1991): "Determination of oxalic acid in air by means of diffusion tubes" in *Science, technology, and European cultural heritage: proceedings of the European symposium, Bologna, Italy, 13-16 June 1989.* BAER N.S., SABBIONI C., SORS André I. (ed)

[22] DE SANTIS Franco, VAZZANA Caterina, MENICHELLI Sabrina, ALLEGRINI Ivo (2003): "The measurement of atmospheric pollutants by passive sampling at the Uffizi Gallery, Florence" in *Analisi di Chimica,* 93, 2003. Società Chimica Italiana

[23] FABRETTI G., SANTIN V. (1991): "Brunelleschi Dome in Sta. Maria del Fiore – Florence. Correlation between the theoretical direct solar radiation and the thermal behaviour obtained through thermographic survey" in *Science, technology, and European cultural heritage: proceedings of the European symposium, Bologna, Italy, 13-16 June 1989.* BAER N.S., SABBIONI C., SORS André I. (ed)

[24] FASCINA Vasco, STEVAN Antonio (1992): "Pioggia e nebbia acida a Venezia in relazione al degrado dei manufatti lapidei" in *3a Conferenza internazionale sulle prove non distruttive, metodi microanalitici e indagini ambientali per lo studio e la conservazione delle opere d'arte: Viterbo 4-9 ottobre 1992.* Istituto Centrale del Restauro | Associazione Italiana Prove non Distruttive Monitoraggio Diagnostica | BetaGamma editrice

[25] FRICKE-BEGEMANN Thomas, GÜLKER Gerd, D. HINSCH Klaus, JOOST Holger, WOLFF Karin (1996): "Detection of plaster detachment in historical murals by TV-holography of wall vibrations" in *5th International Conference on non-destructive testing, microanalytical methods and environmental evaluation for study and conservation of works of art :art '96*, *September 24-28, Budapest, Hungary,* MKE (Hungarian Chemical Society) | AIPnD (Italian Society for Non-destructive Testing Monitoring and Diagnostics) | ICR (Istituto Centrale per il Restauro)

[26] FUCHS D.R., POPALL M., RÖMICH H., SCHMIDT H. (1991): "Preservation of stone glass windows: new materials and techniques" in *Science, technology, and European cultural heritage: proceedings of the European symposium, Bologna, Italy, 13-16 June 1989*. BAER N.S., SABBIONI C., SORS André I. (ed)

[27] FUCHS Dieter, LEISSNER Johanna (1992): "Environmental monitoring using glass sensors: relevant features for small-scale mapping at monuments" in *3a Conferenza internazionale sulle prove non distruttive, metodi microanalitici e indagini ambientali per lo studio e la conservazione delle opere d'arte: Viterbo 4-9 ottobre 1992.*Istituto Centrale del Restauro | Associazione Italiana Prove non Distruttive Monitoraggio Diagnostica | BetaGamma editrice

[28] GAYO Elena, MACIAS Angeles, PALOMO A., GARCIA MORALES Soledad (1992): "Application of infrared thermography to the study of moisture in the cathedral of Toledo" in *3a Conferenza internazionale sulle prove non distruttive, metodi microanalitici e indagini ambientali per lo studio e la conservazione delle opere d'arte: Viterbo 4-9 ottobre 1992.*Istituto Centrale del Restauro | Associazione Italiana Prove non Distruttive Monitoraggio Diagnostica | BetaGamma editrice

[29] GERARDI G. (1994): "Microclimatic survey for the conservation of an open-air fresco" in *4th International Conference non destructive testing of works of art: Berlin 3-8 October 1994.* Istituto Centrale del Restauro | Associazione Italiana Prove non Distruttive Monitoraggio Diagnostica | BetaGamma editrice

[30] GULKER Gerd, HINSCH Klaus, HOLSCHER Claudia, MEINLSCHMIDT Peter, WOLFF Karin (1992): "Monitoring of deformation and deterioration processes in historic buildings by Electronic Speckle Pattern Interferometry" in *3a Conferenza internazionale sulle prove non distruttive, metodi microanalitici e indagini ambientali per lo studio e la conservazione delle opere d'arte: Viterbo 4-9 ottobre 1992.* Istituto Centrale del Restauro | Associazione Italiana Prove non Distruttive Monitoraggio Diagnostica | BetaGamma editrice

[31] HAAGENRUD S.E., HENRIKSEN J.F. (1991): "A continuous monitor for Time of Wetness (TOW) measurements in the micro-environment" in *Science, technology, and European cultural heritage: proceedings of the European symposium, Bologna, Italy, 13-16 June 1989.* BAER N.S., SABBIONI C., SORS André I. (ed)

[32] HESS Peter (1999): "Laser based air pollution monitoring (LARA)" in *Standards, Measurements and Testing – Programme for research and technological development, including demonstration, in the field of standards, measurements and testing 1994-1998*. European Communities

[33] JAMES Julian (1991): "The wall paintings of Horsham St Faith priory: environmental causes of deterioration and their treatment" in *Science, technology, and European cultural heritage: proceedings of the European symposium, Bologna, Italy, 13-16 June 1989.* BAER N.S., SABBIONI C., SORS André I. (ed)

[34] LEFEVRE Roger, BOUGRAIN-DUBOURG R. (1993): "Global study of the atmospheric environment and air pollution in relation to restoring the romanesque portal of the primatial church of Saint-Trophime in Arles, France" in *Conservation of architectural surfaces: stones and wall covering*. Venezia: il Cardo

[35] LEVIN Jeffrey (1994): "America Tropical" in *Conservation: the GCI newsletter, 9, n°2,*1994. The Getty Conservation Institute

[36] LIVINGSTON Richard A. (1992): "The non-destructive measurement of chlorides and moisture in historic masonry using the neutron probe" in *3a Conferenza internazionale sulle prove non distruttive, metodi microanalitici e indagini ambientali per lo studio e la conservazione delle opere d'arte: Viterbo 4-9 ottobre 1992.* Istituto Centrale del Restauro | Associazione Italiana Prove non Distruttive Monitoraggio Diagnostica | BetaGamma editrice

[37] LÖFVENDAHL Runo (1996): "Quantification of salts in outdoor Gotland sandstone sculptural objects in Sweden" in *5th International Conference on non-destructive testing, microanalytical methods and environmental evaluation for study and conservation of works of art :art '96*, *September 24-28, Budapest, Hungary.* MKE (Hungarian Chemical Society) | AIPnD (Italian Society for Non-destructive Testing Monitoring and Diagnostics) | ICR (Istituto Centrale per il Restauro)

[38] LONGONI Antonio (1999): "A new portable x-ray Fluorescence Spectrometer for High Resolution non destructive Analysis of Works of Art" in *Standards, Measurements and Testing – Programme for research and technological development, including demonstration, in the field of standards, measurements and testing 1994-1998*. European Communities

[39] LORUSSO S., MARABELLI M., TROILI M., BIONDI F. (1996): "Air quality of historic cities and deterioration of monuments: case-studies in Rome and Tivoli" in *5th International Conference on non-destructive testing, microanalytical methods and environmental evaluation for study and conservation of works of art :art '96*, *September 24-28, Budapest, Hungary.* MKE (Hungarian Chemical Society) | AIPnD (Italian Society for Non-destructive Testing Monitoring and Diagnostics) | ICR (Istituto Centrale per il Restauro)

[40] MAEKAWA Shin, PREUSSER Frank (1993): "Environmental Monitoring at the Tomb of Nefertari" in *10th Triennal Meeting Washington DC, USA, 22-27 August 1993*. ICOM Committee for Conservation

[41] MAMILLIAN M. (1991): "Methods for assessing the deterioration of stone monuments" in *Science, technology, and European cultural heritage: proceedings of the European symposium, Bologna, Italy, 13-16 June 1989.* BAER N.S., SABBIONI C., SORS André I. (ed)

[42] MARABELLI Maurizio (1992): "Surveys for the control of indoor pollution affecting cultural property in Italy" in *3a Conferenza internazionale sulle prove non distruttive, metodi microanalitici e indagini ambientali per lo studio e la conservazione delle opere d'arte: Viterbo 4-9 ottobre 1992.*Istituto Centrale del Restauro | Associazione Italiana Prove non Distruttive Monitoraggio Diagnostica | BetaGamma editrice

[43] MONTACUTELLI Riccardo, TARSITANI Gianfranco, MAGGI Oriana, GABRIELLI Nazzareno (1992): "Metodi di controllo microbiologico degli affreschi: l'esempio della Cappella Sistina" in *3a Conferenza internazionale sulle prove non distruttive, metodi microanalitici e indagini ambientali per lo studio e la conservazione delle opere d'arte: Viterbo 4-9 ottobre 1992.*Istituto Centrale del Restauro | Associazione Italiana Prove non Distruttive Monitoraggio Diagnostica | BetaGamma editrice

[44] MONTATO M., CALLEJA L., PEREZ GARCIA B., SUAREZ DEL RIO L.M., RUIZ DE ARGANDOÑA, V.G., ESBERT, R.M., GROSSI, C.M. (1991): "Non-destructive ultrasonic procedure to evaluate in situ the relative deterioration of monumental stones: preliminary results" in *Science, technology, and European cultural heritage: proceedings of the European symposium, Bologna, Italy, 13-16 June 1989.* BAER N.S., SABBIONI C., SORS André I. (ed)

[45] PANTANI L., BALLERINI G., BRACCI S., CECCHI G., CHIARI R., EDNER H., LAMENTI G., LOGNOLI D., JOHANSSON T., RAIMONDI V., SUNDNÉR B., SVANBERG S., TIANO P., TIRELLI, D., TOMASELLI L., WEIBRING P. (2000): "Lidar remote sensing: a tool for non-destructive analysis of buildings" in *Science and Technology for the safeguard of Cultural Heritage in the Mediterranean Basin, Proceedings of the second international congress, 5-9 July 1999 Paris.* Elsevier

[46] PAOLETTI D.; SCHIRRIPA SPAGNOLO G. (1991): "Holographic contouring technique for marble erosion measurements" in *Science, technology, and European cultural heritage: proceedings of the European symposium, Bologna, Italy, 13-16 June 1989.* BAER N.S., SABBIONI C., SORS André I. (ed)

[47] PAOLETTI D., SCHIRRIPA SPAGNOLO G. (1995): "The potential of portable TV holography for examining frescoes *in situ*" in *Studies in conservation*, 40, no. 2, 1995

[48] PERUCCA Giancarlo, REBUA Giovanni, MASSA Vincenzo (1992): "Il sistema 'ARA' (Acid Rain Analyser) per l'analisi delle piogge" in *3a Conferenza internazionale sulle prove non distruttive, metodi microanalitici e indagini ambientali per lo studio e la conservazione delle opere d'arte: Viterbo 4-9 ottobre 1992.*Istituto Centrale del Restauro | Associazione Italiana Prove non Distruttive Monitoraggio Diagnostica | BetaGamma editrice

[49] PETERSON Karin, KRUMBEIN Wolfgang (1992): "Comparative studies of the efficiency of non-destructive testing methods of microbial attack on objects of art" in *3a Conferenza internazionale sulle prove non distruttive, metodi microanalitici e indagini ambientali per lo studio e la conservazione delle opere d'arte: Viterbo 4-9 ottobre 1992.* Istituto Centrale del Restauro | Associazione Italiana Prove non Distruttive Monitoraggio Diagnostica | BetaGamma editrice

[50] PITZURRA L., BELLEZZA T., BON DI VALSASSINA C., GARIBALDI V., GIRALDI M., SBARAGLIA G., SPERA G., BISTONI, F. (2000): "Microbial environment monitoring of art museums" in *Science and Technology for the safeguard of Cultural Heritage in the Mediterranean Basin, Proceedings of the second international congress, 5-9 July 1999 Paris.* Elsevier

[51] PIZZIGONI, Guiseppe, PERUCCA Giancarlo, MASSA Vincenzo (1992): "Diagnostica ambientale e materia per la 'Maestà' di Simone Martini" in *3a Conferenza internazionale sulle prove non distruttive, metodi microanalitici e indagini ambientali per lo studio e la conservazione delle opere d'arte: Viterbo 4-9 ottobre 1992.* Istituto Centrale del Restauro | Associazione Italiana Prove non Distruttive Monitoraggio Diagnostica | BetaGamma editrice

[52] PREUSSER Frank (1991): "Scientific and Technical Examination of the Tomb of Queen Nefertari at Thebes" in *The conservation of wall paintings; proceedings of a symposium organized by the Courtauld Institute of Art and the Getty Conservation Institute, London, July 13-16 1987*. The Getty Conservation Institute. CATHER Sharon (ed)

[53] SABBIONI Cristina, PANTANI Marta (2000): "Evaluation of damage in historical buildings: a critical intercomparison of different techniques" in *Science and Technology for the Safeguard of Cultural Heritage in the Mediterranean Basin, Proceedings of the second international congress, 5-9 July 1999 Paris*. Elsevier

[54] SCHILLING Michael R. (1993): "Colour Measurement of the Wall Paintings in the Tomb of Nefertari" in *10th Triennal Meeting Washington DC, USA, 22-27 August 1993*. ICOM Committee for Conservation

[55] SCIUTI S., FRONTEROTTA G., VENDITTELLI M., LONGONI A., FIORINI C. (2001): "A non-destructive analytical study of a recently discovered Roman wall painting" in *Studies in conservation*, 46, no. 2, 2001

[56] TOMASINI Enrico Primo (1999): "LASERART – Non-intrusive laser measurement techniques for diagnostics of the state of conservation of frescoes, paintings and wooden icons" in *Standards, Measurements and Testing – Programme for research and technological development, including demonstration, in the field of standards, measurements and testing 1994-1998*. European Communities

[57] VALENTINI Massimo, SALA Gianni (1992): "Un'indagine mirata alla determinazione dell'umidità e dei flussi di vapore (Cappella Portinari, S. Eustorgio, Milano)" in *3a Conferenza internazionale sulle prove non distruttive, metodi microanalitici e indagini ambientali per lo studio e la conservazione delle opere d'arte: Viterbo 4-9 ottobre 1992*.Istituto Centrale del Restauro | Associazione Italiana Prove non Distruttive Monitoraggio Diagnostica | BetaGamma editrice

[58] WAKEFIELD Rachael Denlse (1999): "On-site monitoring of biological colonisation of stone and plaster surfaces using field portable fluorescence based techniques" in *Standards, Measurements and Testing – Programme for research and technological development, including demonstration, in the field of standards, measurements and testing 1994-1998*. European Communities

[59] WEBER Johannes (1993): "Salt-induced deterioration of Romanesque wall paintings in the church of St. Georgen, Styria, Austria" in *Conservation of architectural surfaces: stones and wall covering*. Venezia: il Cardo

Project no. SSPI-CT-2003-501837-NOAH'S ARK

NOAH'S ARK

GLOBAL CLIMATE CHANGE IMPACT ON BUILT HERITAGE AND CULTURAL LANDSCAPES

Instrument: STREP

Thematic Priority:1.2.1 POLICY-ORIENTED RESEARCH

DELIVERABLE 6

OVERVIEW OF THE EXPECTED NEGATIVE AND POSITIVE CONSEQUENCES OF GLOBAL ENVIRONMENTAL CHANGES ON DETERIORATION OF MATERIALS

Due date of deliverable: 31 May 2006
Actual submission date : June 2006

Start date of project: June 2004 Duration: 3 Years

Corrosion and Metals Research Institute (Sweden)

Project co-funded by the European Commission within the Sixth Framework Programme (2002-2006)		
Dissemination Level		
PU	Public	X
PP	Restricted to other programme participants (including the Commission	
RE	Restricted to a group specified by the consortium (including the Commission	
CO	Confidential, only for members of the consortium (including the Commission Services)	

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1 Introduction

The present report has been produced within WP2: "Prediction of the impact and consequences of climate change on deterioration of building materials". Figure 1 presents an overview of the main activities in WP2 and the relation to WP1 "Determination of meteorological changes critical to the built cultural heritage", which provides the input to WP2. In short, WP1 deals with data and WP2 with models and the combination of these to produce maps. The first objective of WP2, to "develop models for the impact of global climate changes on the deterioration of different cultural heritage materials, including both meteorological and pollution parameters" was presented in deliverable 2 “model for assessment of global changes on different materials”.

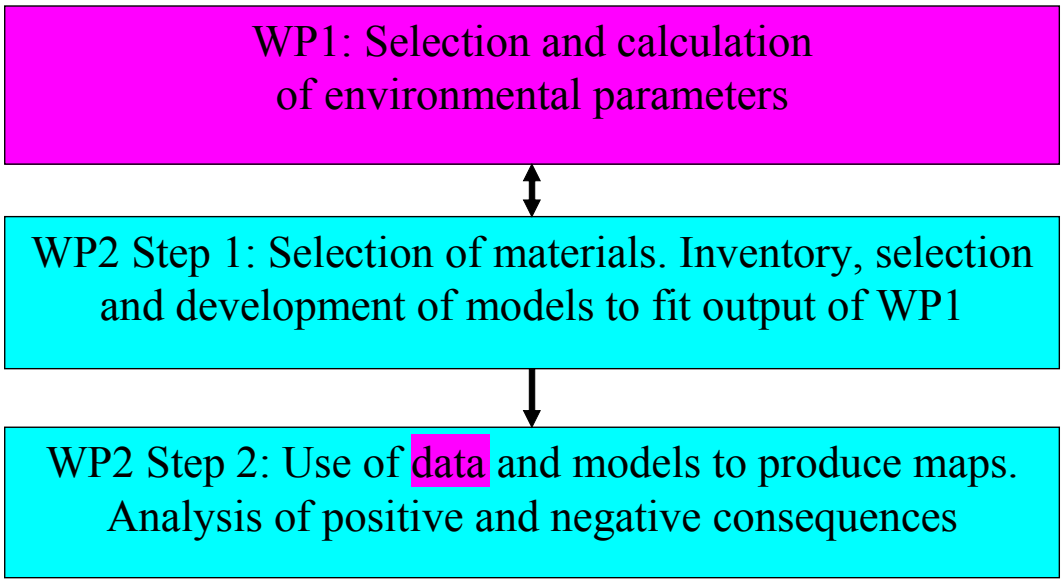

Figure 1. Overview of main activities in WP2.

This report presents the final synthesis of the results and gives an overview of the expected negative and positive consequences of global environmental changes on deterioration of materials. This work will continue with the production of maps to show the most important results in WP7 “climate risk maps and vulnerability atlas for cultural heritage for Europe”.

2 Included materials

This section was included in deliverable 2 and is repeated here for convenience and completeness.

When selecting materials several important criteria need to be considered, for example:

- Availability of dose-response / damage functions
- Frequency of use in European cultural heritage
- Sensitivity to climatic factors

An important aspect in this context is the question on what is considered cultural heritage. In this project a principal decision was made to limit the choice of materials and to exclude modern materials like polymers. This decision was more of a practical nature in order to limit the work and should not constitute a statement on the historical value of objects containing these materials.

Based on the above criteria and several discussions during the first project meetings the following materials were selected for deeper analysis and these are the materials that are treated in this report:

Stone materials
- Marble
- Limestone
- Sandstone
- Lime mortar
- Brick
- Clay containing materials

Metals
- Iron and carbon steel
- Zinc
- Copper
- Bronze
- Lead

Wood

Glass representative of medieval stained glass windows

3 Analysis of negative and positive consequences on the deterioration of materials

3.1 Stone and masonry materials

3.1.1 Chemical attack inducing material dissolution

3.1.1.1. Lipfert function

The damage function proposed by Lipfert (1989) recognizes three mechanisms for material loss:

1. Dissolution in "clean" rain, representing material loss due to the karst effect (pH=5.6).
2. Acceleration of dissolution due to rain acidity caused by air pollutants. It indicates material loss due to the hydrogenionic concentration of the rainwater.
3. Attack by gaseous air pollutants, notably SO_2 and HNO_3. It describes the dry deposition of gaseous pollutants occurring between precipitation events.

$$L = 18.8 \cdot R + 0.016 \cdot [H^+] \cdot R + 0.18 \, (V_{dS} \, [SO_2] + V_{dN} \, [HNO_3])$$

This damage function is valid for precipitation pH in the 3-5 range, where L is the surface recession per year (μm/year), 18.8 is the solubility of $CaCO_3$ in equilibrium with 330 ppm CO_2, R is the rainfall (m/year), 0.016 is the constant valid for precipitation pH in the range 3-5, $[H^+]$ is the ion concentration (ion/l) evaluated from yearly rain pH, 0.18 is the conversion factor from (cm/s) (μg/m^3) to μm, V_{dS} is the deposition velocity of SO_2 (cm/s), $[SO_2]$ is the SO_2 concentration (μg/m^3), V_{dN} is the deposition velocity of HNO_3 (cm/s), and $[HNO_3]$ is the HNO_3 concentration (μg/m^3).

This function, mainly valid for low porous carbonate stones, will be used within the Noah's Ark Project to produce the damage maps of stone erosion on marbles.

The Lipfert function has previously been tested and used to determine the ***erosion index*** of carbonate materials in the Risk Map of Cultural Heritage at the national level (Italy), developed by the Istituto Centrale per il Restauro (ICR, Rome, Italy) (Ministero dei Beni Culturali ed Ambientali-ICR, 1996; http://www.cartadelrischio.org/).

In addition, this function has been tested in Ravenna, Italy, to assess the stone loss due to rain and gas dry deposition on marble as a function of time (Pantani et al., 1998).

In this city an urban air quality network has been in operation since 1974. Weekly amounts of rain, SO_2 and HNO_3 concentrations were therefore available. Data for pH have been obtainable since 1988, and it is known that pH in the Po Valley has steadily decreased over the last two decades. Thus, the mean pH evaluated over the period 1988-1996 was used for the years before 1988, when data were not available, tending to produce an overestimation of the acid rain effect. The gas deposition velocities v_{dS} = 0.38 cm/s and v_{dN} = 0.16 cm/s were adopted following field exposure tests performed by the Authors.

Figure 3.1.1 reports the annual surface loss of marble in Ravenna from 1978 to 1996, which is about 15 μm/y on average; thus, the surface loss over a century is estimated at about 1.5 mm.
Considering separately the single factors contributing to surface loss, 85% of the erosion of a marble surface is due to the karst effect and only 1% is due to acid rain. Thus, the contribution to the loss due to the dry deposition of SO_2 and HNO_3 is about 14%. Figure 3.1.2 reports data on the

respective contributions calculated separately for the two gases at the site of Ravenna. As can be seen, surface loss due to SO_2 was prevalent in the past and has decreased over more recent years, while the loss due to HNO_3 has increased.

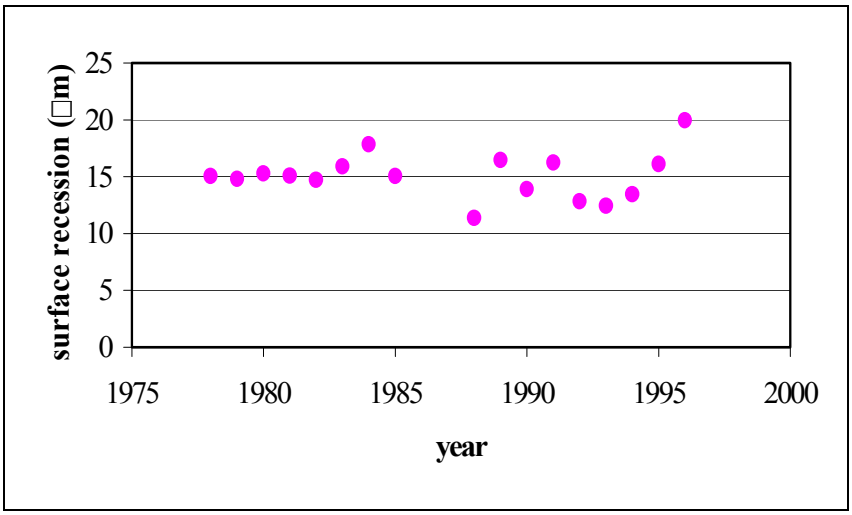

Figure 3.1.1. Surface loss of marble evaluated using the Lipfert damage function at the Ravenna site as a function of time.

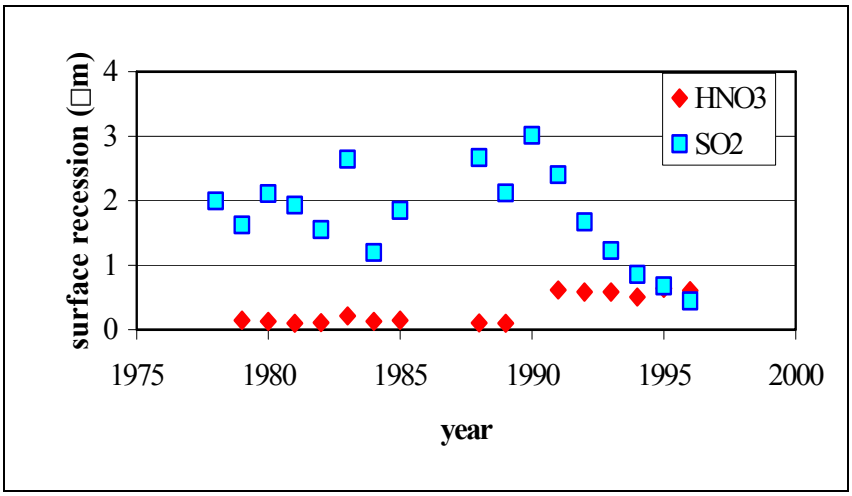

Figure 3.1.2. Surface loss of marble due to HNO_3 and SO_2 deposition evaluated using the Lipfert damage function at the Ravenna site as a function of time.

In conclusion this application of the Lipfert function on marble samples shows that the surface leaching of low porous carbonate materials is mainly due to the "clean" precipitation effect.

According to the precipitation forecast obtained using the HadCM3 model, overall rainfall is likely to decrease slightly in Europe over the next century, especially in the summer months. In particular, yearly precipitation will decrease by about 60-150 mm/y in southern Europe and central Portugal (Figure 3.1.3) While significant changes are not predicted for central Europe and the United Kingdom (Figure 3.1.4), an increase is expected for north-eastern Europe and southern Norway, up to a maximum of 200 mm/y (Figure 3.1.5).

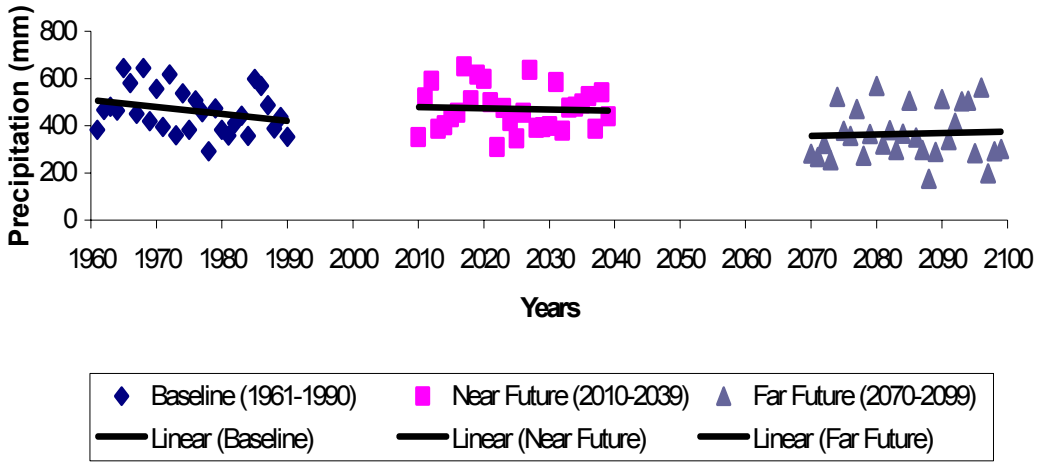

Figure 3.1.3. Annual precipitation predicted in southern Italy (37.5 N, 15 E) for the three periods investigated.

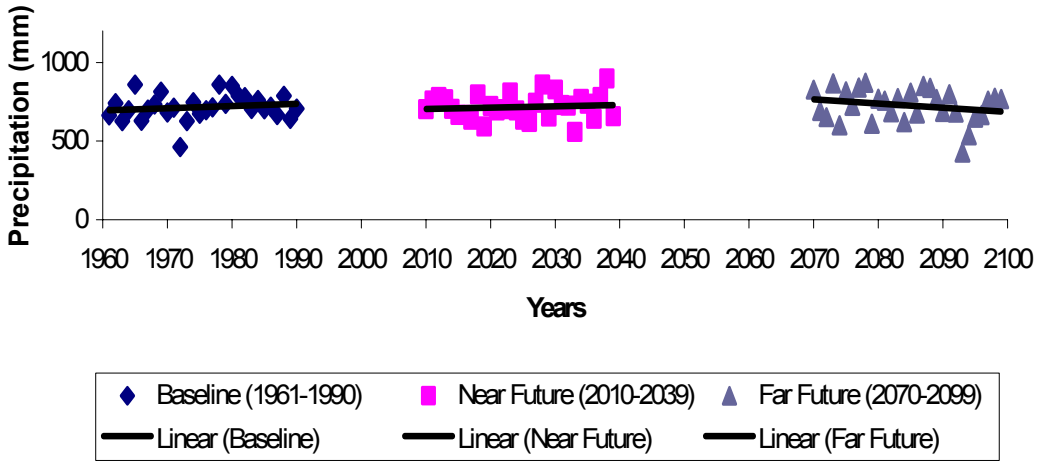

Figure 3.1.4. Annual precipitation predicted in central Poland (52.5 N, 18.75 E) for the three periods investigated.

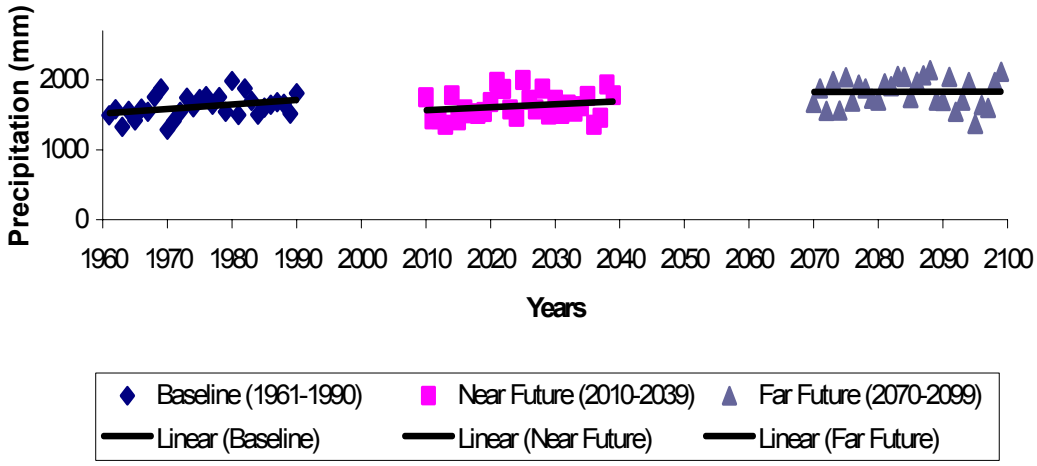

Figure 3.1.5. Annual precipitation predicted in southern Norway (60 N, 7.5 E) for the three periods investigated.

A further important factor to be taken into account is that HadCM3 predicts for the next century an increase in both the frequency of rainy days and the maximum daily rainfall amount. Although the Hadley model is less able to represent extreme events, such episodes constitute a serious threat to the built heritage in the future and therefore require attention.

Introducing the yearly precipitation data of the Hadley model in the part of the Lipfert function related to the "clean rain" effect, L (μm/y) = 18.8 R, information on stone erosion due to the so-called "karst effect" were obtained (Figure 3.1.6). The processing of these data gives a predicted decrease of surface erosion in low porous carbonate stone of about 1-3 μm/y in central Portugal, Greece and Sicily, indicating southern Europe to be an area of decreasing risk. A general risk increase in north-eastern Europe (about 4μm/y in the south of Norway) is predicted, while central Europe and the northern United Kingdom are expected to maintain unchanged risk levels.

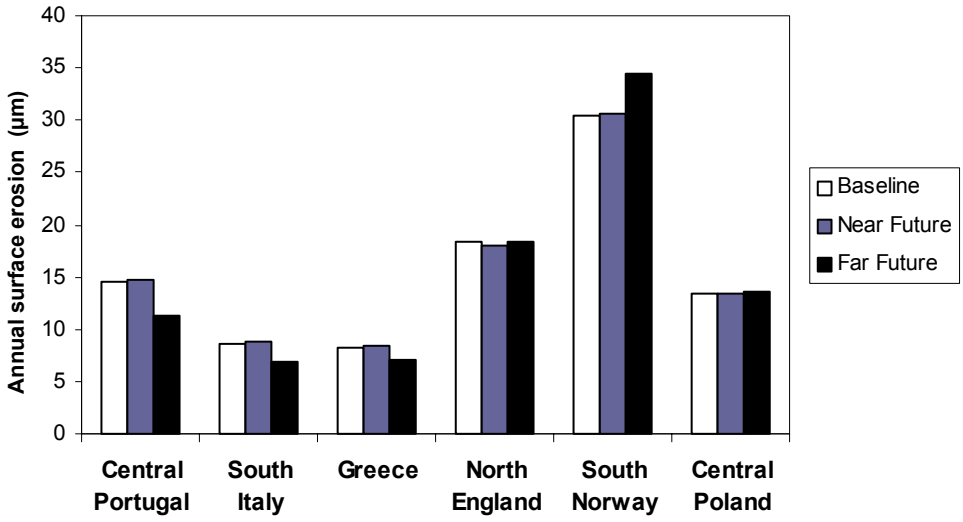

Figure 3.1.6. Annual surface erosion evaluated using a modified Lipfert damage function L (μm/y) = 18.8 R.

3.1.1.2 Damage function from the MULTI-ASSESS project.

The function recently proposed for degradation of limestone after 1 year of exposure from the MULTI-ASSESS project is

$$R = 3.95 + 0.0059[SO_2]RH_{60} + 0.054Rain[H^+] + 0.078[HNO_3]Rh_{60} + 0.0258PM_{10}$$

where R is the surface recession in μm and Rh_{60} is Rh-60 when Rh>60 otherwise 0.

Comparing the "baseline" scenario and the "far future" scenario results in a change in relative humidity between –14% and +4%. For an SO_2 level of 10 μg m^{-3} or an HNO_3 level of 1 μg m^{-3}, this corresponds to changes in corrosion rate less that one μm $year^{-1}$, which is negligible. The change in precipitation is between –300 to +300 mm $year^{-1}$. For a constant pH level of 4.5 this also results in changes in corrosion rate less that one μm $year^{-1}$. It agrees with the conclusions reached by applying the Lipfert function in the previous section, in contrast with the significant chemical effects on metals in combination with climate, discussed below.

3.1.3 Thermoclastism

Concerning thermoclastism, the damage function derived by Lazzarini and Tabasso, 1986 will be applied.

$\sigma = E \cdot \lambda \cdot \Delta T$
where:
σ: internal tension in the material (MPa)
E: modulus of elasticity (GPa)
λ: thermal dilatation coefficient (m/m·C°)
ΔT: Surface maximum daily T– Surface minimum daily T (°C)

The threshold of risk towards thermoclastism for a given material is evaluated through the comparison between the internal tension σ caused by thermal shock and the maximum sustainable compressive load that is specific to that material.

Experimental tests performed by Malaga-Starzec et al. (2002) demonstrated that in undamaged Carrara marbles inter-granular decohesion starts in the 40-50°C surface temperature range. The progressive granular decohesion results in increased porosity and subsequently, through expansion, to loss of strength.

The results showed that most of the expansion occurred along the grain boundaries. Since the total volume of grain boundaries increases with falling grain-size, fine-grained marbles are more sensitive to temperature changes than coarse-grained ones.

Over recent years, interest has focused on the effects of temperature fluctuations on thin (3-4 cm) slabs of marble and limestone used for façade cladding. Shouenburg et al. (2000) indicated that the panels are prone to concave bowing when the temperature difference is relatively high, while convex bowing tends to occur when the temperature difference is below approximately 10-15°C. Moreover samples, with a granoblastic texture showed the greatest degree of bowing.

Thus, the Lazzarini and Tabasso function will be used mainly for mapping surface damage due to heating and cooling cycles taking place on marbles, one of the materials most sensitive to this damage process.

Data for the thermal dilatation coefficient, compressive strength and modulus of elasticity for each material are available in the literature (Dal Prà, 1987; Nicholson and Nicholson, 2000). By contrast, maximum and minimum daily temperatures at the material surface are critical values that are not available from climate data, which instead provide mean monthly/seasonal/yearly data of the air temperature.

For this purpose, experimental data produced within the project "Environmental Monitoring at Hagar Qim and Mnajdra Temples" in Malta, funded by Heritage Malta, are currently under processing in order to obtain an indication of the degree of thermal stress undergone by the Megalitic temples. Preliminary results show a surface daily temperature range between 23°C in July and 28 °C in September in south-eastern exposed surface, which are critical values for damage due to thermoclastism. The daily air temperature range measured reaches a maximum of 8°C in September (Table 3.1.1).

Table 3.1.1. Experimental data of air and surface daily temperature for a south-eastern exposed surface at Hagar Qim and Mnajdra Temples in Malta.

Date	Air Tmax (°C)	Air Tmin (°C)	Daily ΔT air (°C)	Surf. Tmax (°C)	Surf. Tmin (°C)	Daily ΔT surf. (°C)
29 June 05	28.1	24.2	3.9	46.3	23.0	23.3
01 July 05	32.3	24.7	7.6	48.1	25.3	22.8
27 Sept. 05	26.2	19.3	6.9	42.1	14.6	27.5
29 Sept. 05	26.8	18.5	8.3	44.0	15.0	29.0

The results provide clear evidence that surface temperature depends mainly on solar radiation, therefore presenting different values according to the direction of surface exposition. South-east exposed surfaces generally experience a higher daily surface temperature range than north-facing ones. The weather conditions strongly influence the trends, which show lower daily amplitudes when the sun is not at its maximum or is randomly shadowed by clouds. Wind presence is also an important parameter.

Forecasts indicate Europe undergoing warming in all seasons, in the range of 2.5 to 5.5°C, even if a very large increase in summer temperatures is likely to affect particularly the Mediterranean area (reaching 10°C). Data provided by WP1 evidences the number of thermal shocks > 20°C per year increasing in the Mediterranean area, especially in the far future.

Concerning solar radiation, Wild et al. (2005) present data suggesting that the widespread decline of solar radiation widely reported for the period from about 1960 to 1990 did not continue in the following years. On the contrary, there are indications that the amount of sunlight at the surface has increased during the 1990s, and will probably continue to do so in coming years. This finding obviously refers to clear sky conditions.

All the research work performed so far indicates the Mediterranean area as the one continuing to be most affected by thermoclastism. The Noah's Ark Project will devote more efforts to understand better of the relationship between air temperature and surface temperature for future previsions, performing a statistical processing of the experimental data provided by the research project in Malta. The objective is to make optimum use of the proposed function.

3.1.4 Cryoclastism: freeze-thaw cycles effect

Often the most evident signs of climate weathering in cooler regions are frost damage. This is caused when wet stone freezes and the associated volume change causes the outer layers to shatter.

Climates of the past were quite different. The weather in the Early Modern Period was so different that the climatologist Hubert Lamb popularised the term *Little Ice Age* although modern scholarship has made this period less easy to define. It is also possible that it was a good deal stormier and Glasser et al. (1999) have argued there were periods of notable storminess in the Adriatic Sea and in Spain making stone wetter and thus more prone to damage on freezing.

The influence European temperature on the deterioration process might be seen as relatively slight because it is hard to imagine just few degrees would lead to a significant change in the rate of deterioration of heritage. However, there are factors which serve to enhance the impact of small changes. The number of freeze-thaw cycles is especially sensitive to temperature and the likely reduction in freezing across much of Europe in the future will lower the potential for frost shattering of porous building stone. This can be seen from historical records.

Much of the early work in establishing past climate was based on descriptive records, but a more quantitative picture is possible for temperature changes over the last three hundred years. Often daily records survive for much of this period, so one can estimate the likely number of freeze-thaw cycles (Brimblecombe & Camuffo 2003). Long term changes in the annual number of freeze-thaw events for central England are shown in Fig. 3.1.7. Here, colder weather two centuries back meant that there were more freeze-thaw cycles.

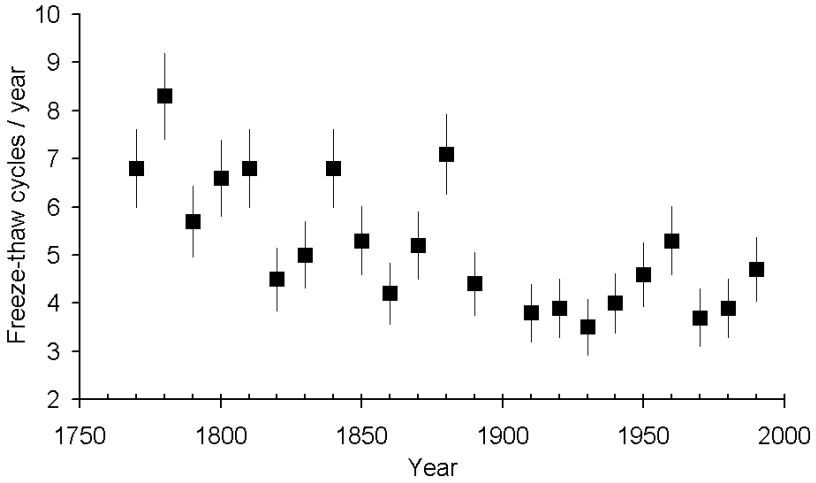

Figure 3.1.7. Historical records London

The largest number of cycles is typically experienced by climates that hover close to zero degrees. Figure 3.1.8 shows that the number of freeze-thaw cycles is likely to decrease in the future in the regions of both Central England (maritime) and Czech Republic (continental). It is also clear that the milder climate of England is subject to less freeze-thaw events throughout the period.

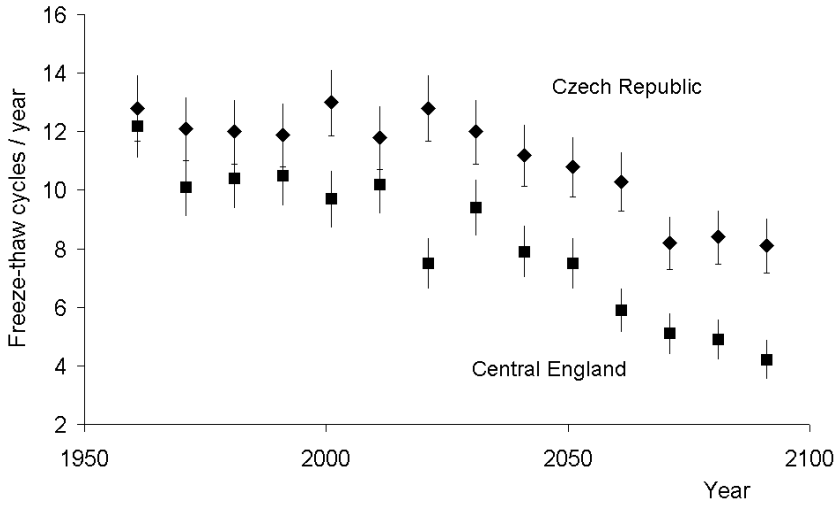

Figure 3.1.8. Number of freeze-thaw cycles each year as predicted for Hadley grid squares representing the Czech Republic and central England. The values displayed are decadal averages.

It is likely that northern climates may have been so cold in past centuries that they experienced fewer freeze thaw cycles, thus in the future freeze-thaw events may be more frequent. Figure 3.1.9, shows the strong contrast between the Central England region and Narssarssuaq, Greenland.

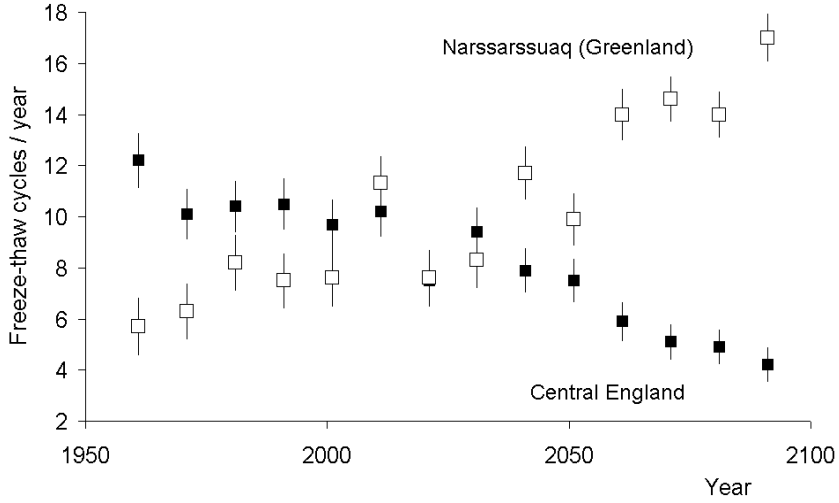

Figure. 3.1.9. Number of freeze-thaw cycles each year as predicted for Hadley grid squares representing the area of Narssarssuaq (Greenland) and Centra; England. The values displayed are decadal averages.

Furthermore in the far north, increasing temperatures threatens to melt the upper layers of permafrost or to induce freeze-that cycles which can disrupt the structure of soils and damage archaeological and paleoecological remains well preserved in the permafrost (Davis et al. 2000; Viles, 2002). As an example calculations from the Hadley model suggest a four fold increase in the number of days above freezing at Narssarssuaq in Greenland (Brimblecombe et al. 2006; Grossi et al. 2006).

Viles (2002) pointed out that most physical temperature related weathering processes require not only cycling of temperature to produce decay, but also moisture. Changes in rainfall may be critical altering the water supply. In the NOAH's ARK project we have defined a climatic parameter named "wet-frost days" as number of days of freezing weather (i.e. below 0^oC) that follow days of rain. Different parts of Europe will experience different changes. We note for example that there is a potential for wetter frosts days in future parts of East Europe although the number of events of wet frosts each year is rather small, only one or two each year (Grossi et al. 2006). Viles (2002) also hints at the possibility of future wet-frost increase in northern hemisphere high latitudes.

In NOAH's ARK, we are also interested in transitions between 1 and -3^oC, which are likely to give severe damage. Damage has been investigated using the work of Walder & Hallet (1985), They defined temperature ranges that promoted crack propagation when temperature (T, ^oC) is sustained in particular rocks and we adopted the equation Crack length ~ $-0.14T^2 - 2.54T - 8$, where T is between -4^oC and -15^oC from their work. Note that significant crack growth occurs between -4 and -15^oC, but this parameter may well over estimate the crack propagation in dry cold climates.

3.1.5 Mechanical damage in clay containing materials

The principal mechanism by which clay containing materials deteriorate involves swelling and shrinkage of the clayey binder induced by cycles of wetting and drying. On wetting the material expands and on drying it returns to the initial state. The dimensional change determined for a typical sandstone with clayey binder - the Salamanca sandstone from Spain – in response to cycles of wetting and drying is shown in Figure 3.1.10.

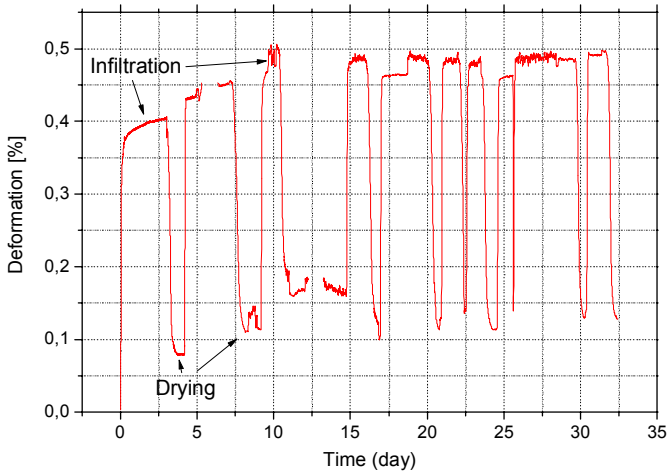

Figure 3.1.10. Cyclic swelling and shrinkage of the Salamanca sandstone with clayey binder subjected to a number of wet-dry cycles.

As one can see, the hygric expansion is partly irreversible: the material remains expanded after drying. Initially with each wetting/drying cycle the irreversible expansion of the material increases. However, after a certain critical number of cycles, an irreversible expansion reaches a saturation level. In the case of the Salamanca sandstone used as the test material this number was 6.

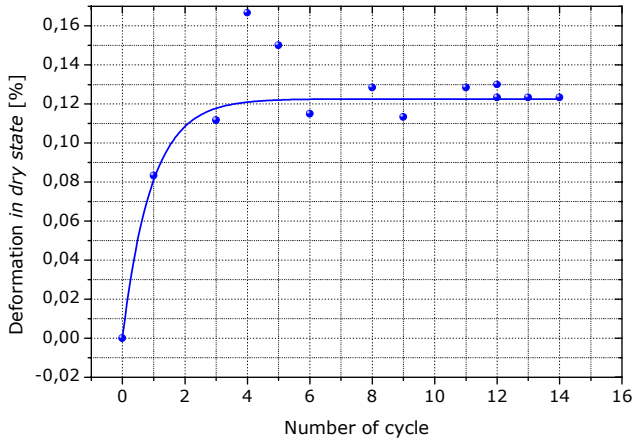

Figure 3.1.11. After 6 wet-dry cycles the irreversible expansion of the Salamanca sandstone reached a saturation level.

It has been assumed that this saturation expansion correlates with the maximum loosening and weakening of the internal structure of the material. Moreover, the cyclic swelling and shrinkage

under the real world conditions is restricted to an outer layer of the stone block. This may cause shear stress at the interface between this surface layer and the bulk of the stone which does not undergo dimensional change. The stress can lead to the loss of cohesion of an outer layer. Both forms of decay i.e. granular disintegration of the stone (sanding) and delamination of the outer layer are observed for clay containing stones in reality.

Basing on the damage mechanism described above, the following procedure has been used within the current project to provide the damage index. Water infiltration into the sandstone was modelled using a coefficient of capillary transport experimentally obtained. In this way wet-dry cycles could be calculated numerically from outdoor precipitation events as well as the thickness of the stone layer in which the cycles occurred. The risk index of the climate induced damage was defined as:

thickness of the outer layer of stone within which the number of wet - dry cycles was greater than 5 during a given time interval (one quarter in the present calculations), and simulatanously the ambient temperature was above 0 ^{o}C.

It is obvious that the risk index is sensitive to the precipitation pattern. The damage will be enhanced if the total time of wetness is divided into as many as possible wetting events followed by drying periods. Therefore an additional analysis of precipitation pattern was undertaken to increase the reliability of predictions:

- maximum precipitation volume was plotted as a function of number of rainy days in a quarter (Figure 3.1.12). The plot was produced from the data predicted for the entire geographical area used in modelling (excluding seas) and the entire periods of 1969-1990, 2010-2039 and 2070-2099 considered. A linear relationship was found, and average maximum rain intensity per day was 8 mm/day. It was assumed that it rained for the whole 24 hours during the days with the maximum precipitation volume. Subsequently, an average rain intensity per hour could be calculated.

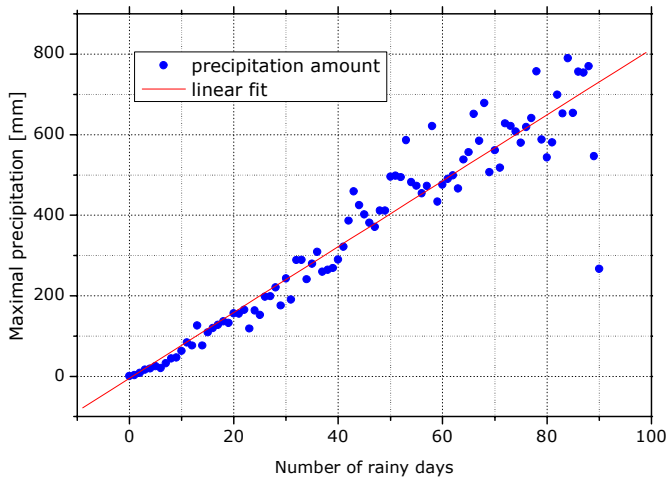

Figure. 3.1.12. Maximum precipitation volume as a function of number of rainy days in a quarter for the entire geographical area used in modelling (excluding seas) and all periods considered.

- using the hourly intensity of precipitation, number of hours during which it rained was calculated for each quarter and each geographical location in terms of grid cells. Then the hours were divided equally between the number of rainy days and dry spells between them were maximised.

- Precipitation volumes were plotted as a function of number of rainy days for 3 locations representing South, West and Central Europe (Figure 3.1.13). It is evident from the plot that the daily precipitation intensities are similar for these different geographic areas, which confirms the validity of the calculation.

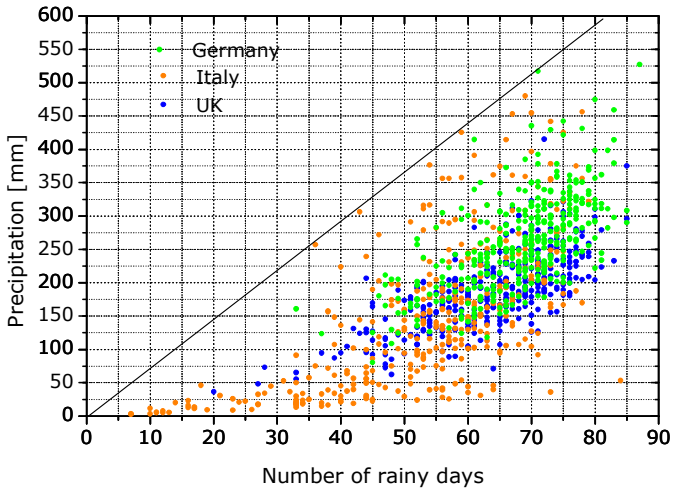

Figure 3.1.13. Precipitation volumes as a function of number of rainy days for three different geographical locations.

The precipitation patterns established in the way described above were used to calculate the risk index. As one can see from Figure 3.1.13 sandstones containing clay will experience more then 5 cycles at depth of several centimetres for most of Europe. Only areas of low temperature or dry conditions are less endangered.

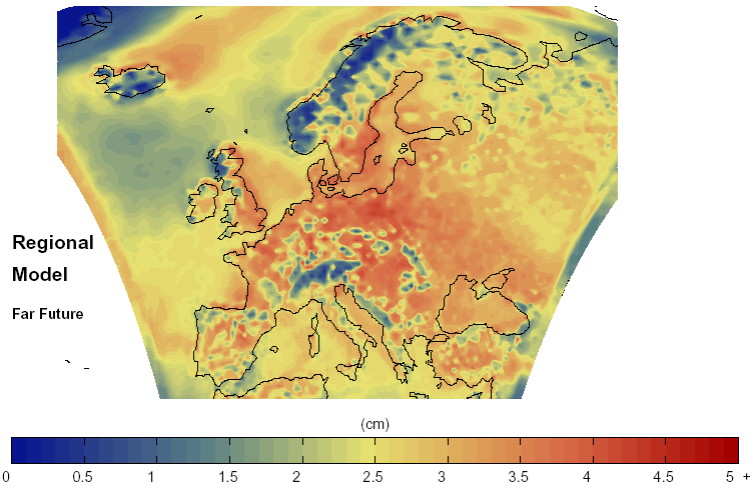

Figure 3.1.12. Thickness of the outer layer of the clay containing sandstone which will experience more than 5 wet - dry cycles per a quarter.

However, an increase in the risk of mechanical damage for clay containing sandstones is especially pronounced in the northern part of Europe (Sweden, Finland and Russia) where it can be up to 100% over coming 100 years. The tendency is mainly due to an increase in precipitation and temperature. In the southern part of Europe (Spain, Italy, Turkey) and Africa the risk will be reduced by about 10-20%

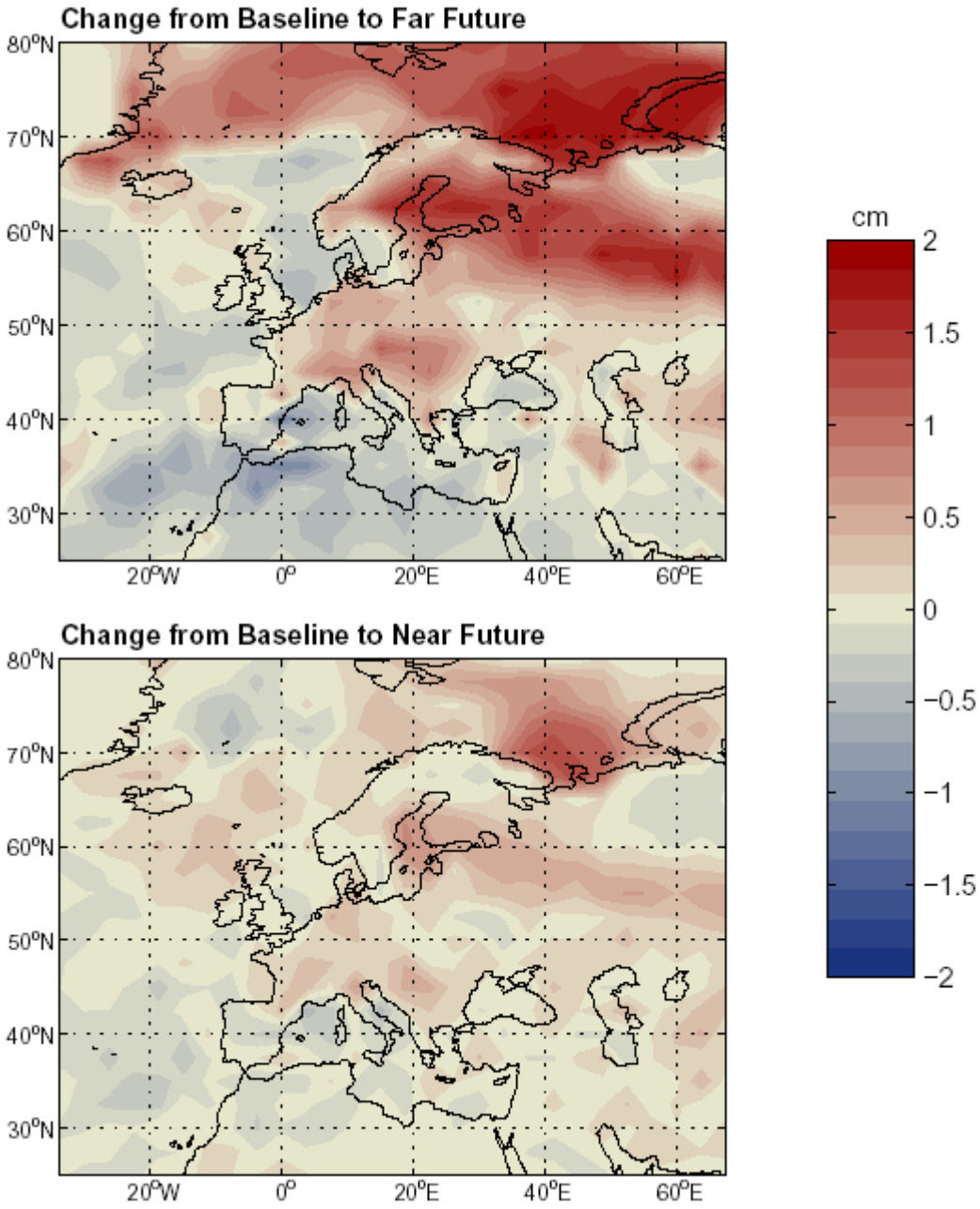

Figure 3.1.13. Calculated change in the risk of mechanical damage of the clay containing sandstone expressed as thickness of the outer layer of the material which will experience more than 5 wet - dry cycles per year.

3.2 Metals

An overview of functions was presented in the Deliverable 2: Model for assessment of effects of global changes on different materials. The following functions for metals were all related to the chemical attack resulting in calculated corrosion attack after 1 year of exposure in µm

$$r_{steel} = 1.58[SO_2]^{0.52} \cdot e^{0.020Rh+f(T)} + 0.166Rain[H^+] + 0.0761PM10 + 0.102D_{Cl}{}^{0.62} \cdot e^{0.033Rh+0.040T}$$
$$f(T) = 0.150(T-10) \text{ when } T<10°C, \text{ otherwise } -0.054(T-10)$$

$$r_{zinc} = 0.196[SO_2]^{0.22} e^{0.018Rh+f(T)} + 0.00406Rain[H^+] + 0.192[HNO_3] + 0.0175D_{Cl}{}^{0.57} \cdot e^{0.008Rh+0.085T}$$
$$f(T) = 0.062(T-10) \text{ when } T<10°C, \text{ otherwise } -0.021(T-10)$$

$$r_{copper} = 0.000302[SO_2]^{0.32}[O_3]^{0.79}Rh \cdot e^{f(T)} + 0.00560Rain[H^+] + 0.0125D_{Cl}{}^{0.27} \cdot e^{0.036Rh+0.049T}$$
$$f(T) = 0.083(T-10) \text{ when } T<10°C, \text{ otherwise } -0.032(T-10)$$

$$r_{bronze} = 0.0255 r_{steel}$$

$$r_{lead} = (0.0125D_{Cl}{}^{0.27} \cdot e^{0.036Rh+0.049T} + 0.0175D_{Cl}{}^{0.57} \cdot e^{0.008Rh+0.085T}) / 2$$

where all environmental parameters are given as averages over a period of one year and

$[SO_2]$ = SO_2 concentration / µg m^{-3}
$[HNO_3]$ = HNO_3 concentration / µg m^{-3}
$[O_3]$ = O_3 concentration / µg m^{-3}
T = Temperature / ^oC
Rh = Relative humidity / %
Rain = Amount of precipitation / mm $year^{-1}$
$[H^+]$ = H^+ concentration of precipitation / mg l^{-1}
D_{Cl} = Chloride deposition / mg m^{-2} day^{-1}
PM10 = concentration of particulate matter > 10 µm / µg m^{-3}

In the following the metals steel, zinc and copper will be analysed in more detail. Based on these results it is then possible to infer the positive and negative consequences for bronze, using the steel results and lead, using the copper and zinc results for the chloride deposition effect.

Looking at the dose-response functions given above it is obvious that the calculated corrosion values will depend on a combination of climatic and pollution parameters that are closely interlinked and not easily separated. As part of the NOAHs ARK project a special sub-contract was given to the Swedish Meteorological and Hydrological Institute (SMHI) with the aim to obtain scenario data on the pollution parameters SO_2, O_3, HNO_3 and pH. That scenario is separate from the scenario used for obtaining temperature, relative humidity and precipitation data (HadCM3 and HadRM3). Since the aim of the NOAHs ARK project is mainly to evaluate possible consequences of the effect of global climate change, other constant pollution scenarios has also been evaluated. Otherwise the quite optimistic SMHI scenario, in terms of pollutant reductions, will shield the possible consequences of climate change.

Another important aspect of the evaluation is the effect of geographical scale. For the climatic parameters the HadCM3 grid with 2.5^o x 3.75^o resolution may be sufficient for capturing the relevant conditions for the objects of cultural heritage. These are, however, often located in cities where the pollutant levels differ quite substantially from the levels in the surrounding rural areas.

Due to a pure area effect the large grid resolution leads to pollutant values that are more similar to rural values than urban values. Therefore calculations based on the SMHI pollutant scenarios tend to underestimate the corrosion values. Maps can also be produced by assuming a constant pollutant level. Instead of trying to estimate an area-based average of the grid cell this approach focuses on the more polluted areas where cultural heritage objects are at risk. Also, in this case the calculated corrosion values are not representative for the entire grid cell. In other words, the variation in pollution within a HadCM3 grid is so substantial that it is not possible to represent all conditions within the cell with a single value and therefore different pollution scenarios are necessary in order to identify the most significant risks to cultural heritage.

The functions presented above combines several distinguishable effects: SO_2, HNO_3, acid rain, particulate matter and chloride deposition. The first step in this analysis has been to investigate these terms individually in order to produce a ranking of effects and to identify the most important effects. The results are shown in Table 3.2.1 using both SMHI scenarios and constant pollution scenarios as indicated above. In order to illustrate the independent SO_2 effect of the SMHI scenario a constant climate scenario has also been investigated. The table has been organised according to the different effects and these will now be discussed individually.

Effect of climate in combination with SO_2

In all cases where the SMHI scenario is used (Table 3.2.1), the consequence of global climate change is negligible since the trend in corrosion is dominated by the predicted pollutant reductions where SO_2 reductions is responsible for most of the decrease as is also evident from the constant climate scenario (T = 10°C, Rh = 75%). The main improvement is from the baseline to the near future. This is not surprising considering that the baseline covers the period 1961-1990 when the pollutants were still very high in Europe compared to the situation today. The SO_2 concentration is still decreasing in some areas but for many cities, the SO_2 concentration has reached a constant value as is illustrated in figure 3.2.1. The alternative scenario with SO_2 equal to 10 µg m^{-3} gives another picture where the corrosion increases or decreases depending on the geographical location and depending on the trends in temperature and relative humidity.

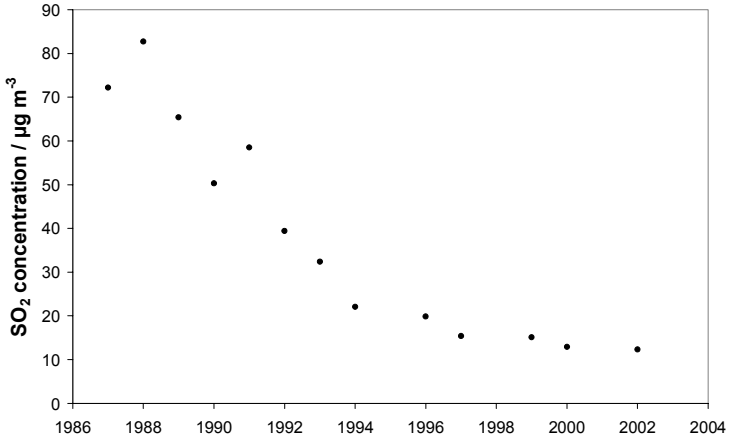

Figure 3.2.1. Trend in SO_2 concentration measured at the ICP Materials test site in Milan, Italy.

Table 3.2.1. Differences in corrosion rates calculated using different parts of the dose-response functions and based on selected pollution and climate scenarios

0: No or small change in corrosion;
+: corrosion increases or remains unchanged depending on the geographical location; ++: substantial change
–: corrosion decreases or remains unchanged depending on the geographical location; – –: substantial change
±: corrosion increases or decreases depending on the geographical location; ± ±: substantial change

Metal	Evaluated term of the Dose-response function	Pollution scenario	Climate scenario	Near - Base difference[a]	Far - Base difference[b]
Carbon steel	$1.58[SO_2]^{0.52}\cdot e^{0.020Rh+f(T)}$	SO_2 = 10 µg m^{-3}	HadCM3	±	± ±
Zinc	$0.196[SO_2]^{0.22}e^{0.018Rh+f(T)}$	SO_2 = 10 µg m^{-3}	HadCM3	0	±
Copper	$0.000302[SO_2]^{0.32}[O_3]^{0.79}Rh\cdot e^{f(T)}$	SO_2 = 10 µg m^{-3}, O_3 = 50 µg m^{-3}	HadCM3	0	±
Carbon steel	$1.58[SO_2]^{0.52}\cdot e^{0.020Rh+f(T)}$	SMHI	HadCM3	– –	– –
Zinc	$0.196[SO_2]^{0.22}e^{0.018Rh+f(T)}$	SMHI	HadCM3	– –	– –
Copper	$0.000302[SO_2]^{0.32}[O_3]^{0.79}Rh\cdot e^{f(T)}$	SMHI	HadCM3	– –	– –
Carbon steel	$1.58[SO_2]^{0.52}\cdot e^{0.020Rh+f(T)}$	SMHI	T = 10 °C, Rh = 75%	– –	– –
Zinc	$0.196[SO_2]^{0.22}e^{0.018Rh+f(T)}$	SMHI	T = 10 °C, Rh = 75%	– –	– –
Copper	$0.000302[SO_2]^{0.32}[O_3]^{0.79}Rh\cdot e^{f(T)}$	SMHI	T = 10 °C, Rh = 75%	– –	– –
Zinc	$0.192[HNO_3]$ = f(T,Rh,NO_2,O_3)	NO_2 = 60 µg m^{-3}, O_3 = 50 µg m^{-3}	HadCM3	0	0
Carbon steel	$0.166Rain[H^+]$	pH = 4.5	HadCM3	0	0
Zinc	$0.00406Rain[H^+]$	pH = 4.5	HadCM3	0	0
Copper	$0.00560Rain[H^+]$	pH = 4.5	HadCM3	0	0
Carbon steel	$0.166Rain[H^+]$	SMHI	HadCM3	–	–
Zinc	$0.00406Rain[H^+]$	SMHI	HadCM3	0	0
Copper	$0.00560Rain[H^+]$	SMHI	HadCM3	–	–
Carbon steel	$0.102D_{Cl}^{0.62}\cdot e^{0.033Rh+0.040T}$	D_{Cl} = 3 mg m^{-2} day^{-1}	HadCM3	0	0
Zinc	$0.0175D_{Cl}^{0.57}\cdot e^{0.008Rh+0.085T}$	D_{Cl} = 3 mg m^{-2} day^{-1}	HadCM3	0	0
Copper	$0.0125D_{Cl}^{0.27}\cdot e^{0.036Rh+0.049T}$	D_{Cl} = 3 mg m^{-2} day^{-1}	HadCM3	0	+
Carbon steel	$0.102D_{Cl}^{0.62}\cdot e^{0.033Rh+0.040T}$	D_{Cl} = 300 mg m^{-2} day^{-1}	HadCM3	±	± ±
Zinc	$0.0175D_{Cl}^{0.57}\cdot e^{0.008Rh+0.085T}$	D_{Cl} = 300 mg m^{-2} day^{-1}	HadCM3	+	+ +
Copper	$0.0125D_{Cl}^{0.27}\cdot e^{0.036Rh+0.049T}$	D_{Cl} = 300 mg m^{-2} day^{-1}	HadCM3	±	±

[a]Difference between near future (2010-2039) baseline (1961-1990)
[b]Difference between far future (2070-2099) baseline (1961-1990)

This is illustrated in figure 3.2.2. The pattern is similar for all materials with a band in the middle of Europe separating the increasing corrosion trend in the north from the decreasing corrosion trend in the south and is most prominent for carbon steel. It is dominated by the temperature effect illustrated schematically in figure 3.2.3. A maximum is observed at about 10 °C. The increasing part (a) can be related to the increased time of wetness. The decreasing part (b) is attributed to a faster evaporation of moisture layers e.g. after rain or dew periods and a surface temperature above the ambient temperature due to sun radiation which result in a decrease of the surface time of wetness.

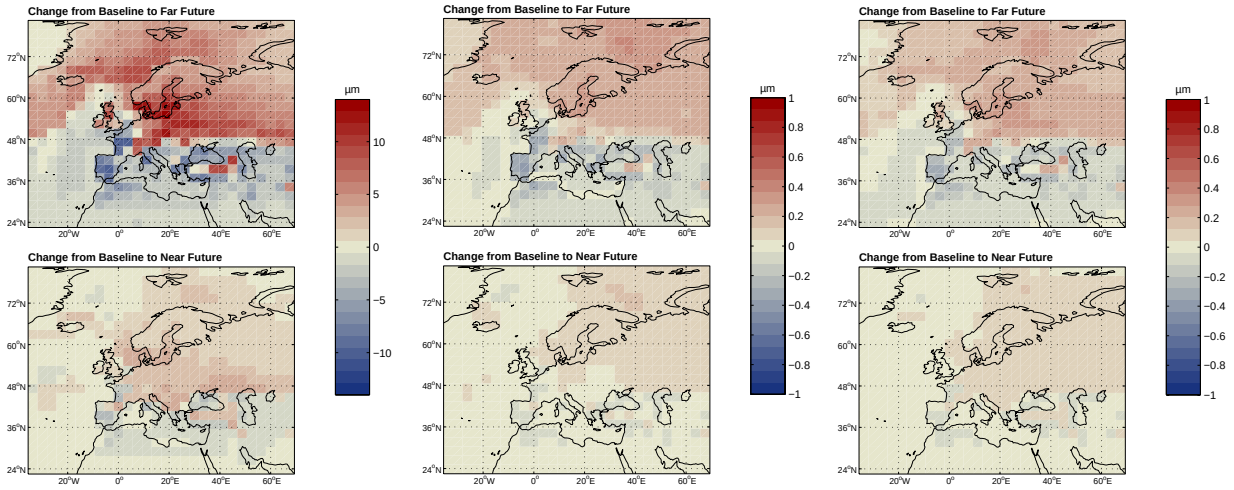

Figure 3.2.2. Calculated change in corrosion rate for carbon steel (left), zinc (middle) and copper (right) due to SO_2 deposition assuming a constant SO_2 level of 10 µg m^{-3}.

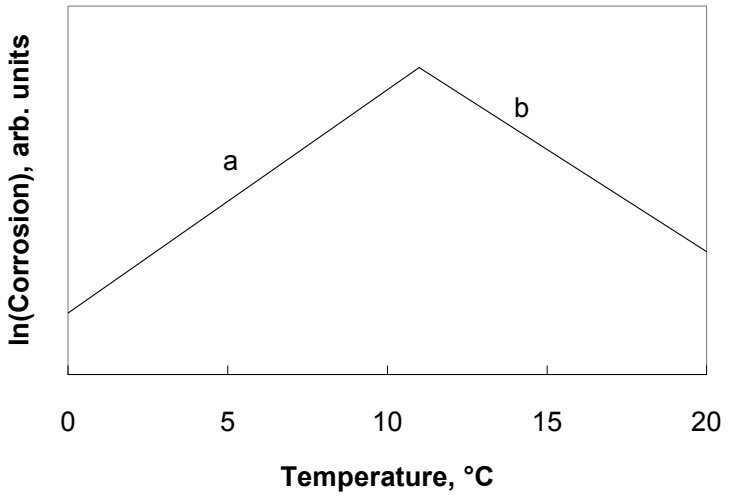

Figure 3.2.3. Schematic representation of the observed temperature dependence for carbon steel, zinc and copper: a) increase of corrosion with temperature in the low temperature range and b) decrease of corrosion with temperature in the high temperature range.

The temperature dependence illustrated in figure 3.2.3 is exemplified in figure 3.2.4 by selecting three grids from figure 3.2.2 for carbon steel. These grids are denoted “Riga”, “London” and “Rome” for ease of identification since these cities are located within the selected grids. The results show that if the pollution situation remains unchanged the effect of global climate change will be significant. The corrosion in the London grid remains high since the temperature changes from about 8 ^{o}C to about 12 ^{o}C (see figure 3.2.3) while “Rome” is replaced by “Riga” as a climate resulting in high corrosion in combination with SO_2.

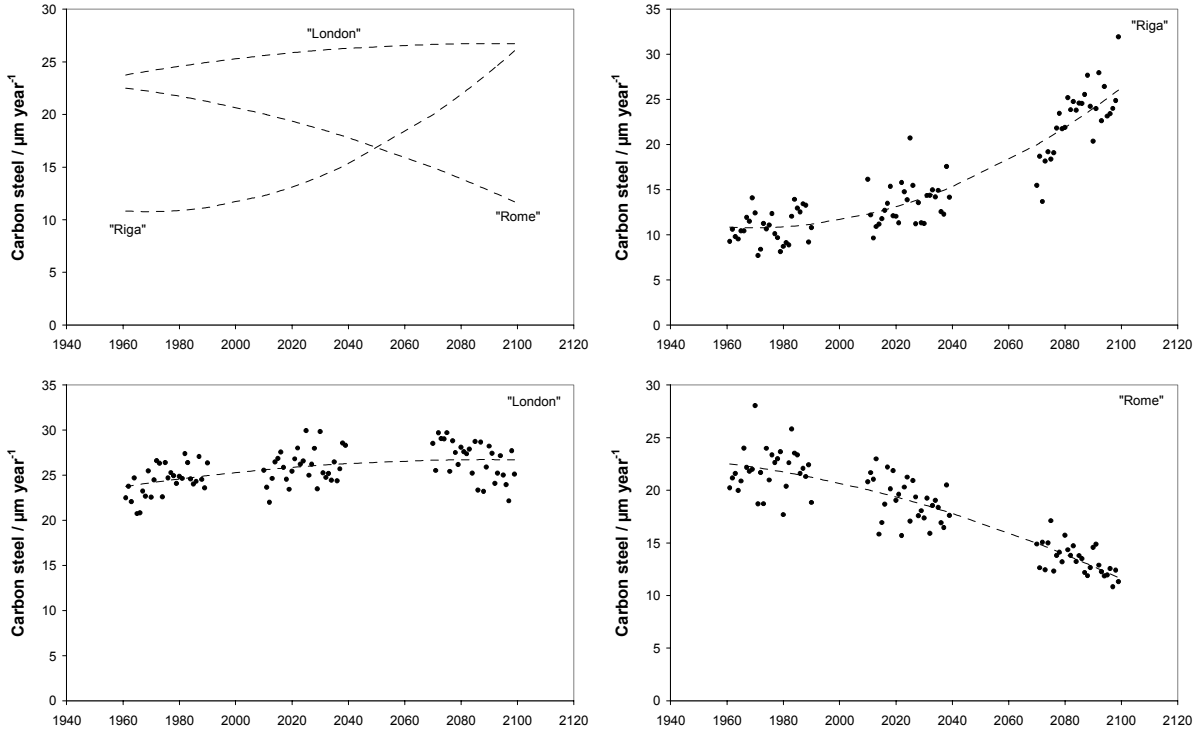

Figure 3.2.4. Calculated corrosion of carbon steel due to SO_2 deposition assuming a constant SO_2 level of 10 µg m^{-3}. Results for three grid cells are given, in which the cities of Riga, London and Rome are located. The upper left figure shows all fitted lines for ease of comparison.

Effect of climate change indirectly in connection with nitric acid production

The following relation was described in deliverable 2 which predicts the annual HNO_3 concentration in terms of NO_2, O_3, Rh and T

$$HNO_3 = 512e^{-3400/(T+273)}\cdot(Rh[O_3][NO_2])^{0.5}$$

The possible effect of changing temperature and relative humidity levels, assuming constant levels of O_3 and NO_2, was evaluated and given in table 3.2.1 for zinc, which is the only metal where HNO_3 is included in the dose-response function. As it turns out this indirect effect of temperature and relative humidity is insignificant.

Effect of acid rain

The results presented in table 3.2.1 based on dose-response function developed from European data show a very small effect of acid rain. However, results from exposure programmes in Asia and in particular China indicate that acid rain could have a much larger effect in warm regions, in particular for copper and zinc. At present stage, no dose-response functions exist that enables quantification of this effect and further research is needed. It is therefore premature to dismiss completely possible effects of climate change in combination with acid rain.

Effect of climate in combination with chlorides

Besides SO_2, chloride deposition is the other important effect that results in possible consequences of global climate change as is seen in table 3.2.1. The deposition level chosen to illustrate the effects (300 mg m^{-2} day^{-1}) is relatively high and can be reached within hundreds of meters from the sea shore or in areas where salting of the roads are in effect. As for the effect of SO_2, the corrosion increases or decreases depending on the geographical location, except for zinc, where increases in corrosion are observed everywhere. This is illustrated figure 3.2.5. The pattern for carbon steel and copper is similar while the pattern for zinc differs. For carbon steel (see figure 3.2.6) and copper the effect of relative humidity and temperature is of equal importance and the decreasing trend in relative humidity tend to balance the increasing trend in temperature. In the case of zinc (see figure 3.2.7), on the other hand, the effect of temperature is dominating and an increasing trend in corrosion due to increasing temperature is observed everywhere.

It is important to stress that this increase of corrosion in areas with high deposition of chlorides is predicted for a *constant* chloride deposition. However, it is also possible that the chloride deposition level will change due to environmental changes in wind strength and wind patterns and this will increase the corrosion even more. A detailed discussion on this possible effect is given in section 3.6.

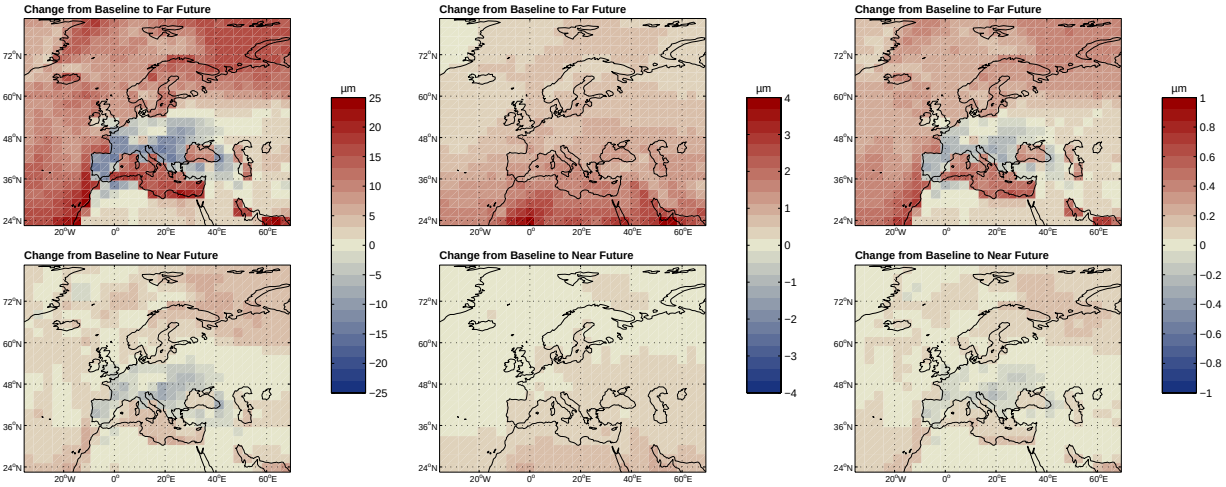

Figure 3.2.5. Calculated change in corrosion rate for carbon steel (left), zinc (middle) and copper (right) due to chloride deposition assuming a constant chloride deposition of 300 mg m^{-2} day^{-1}.

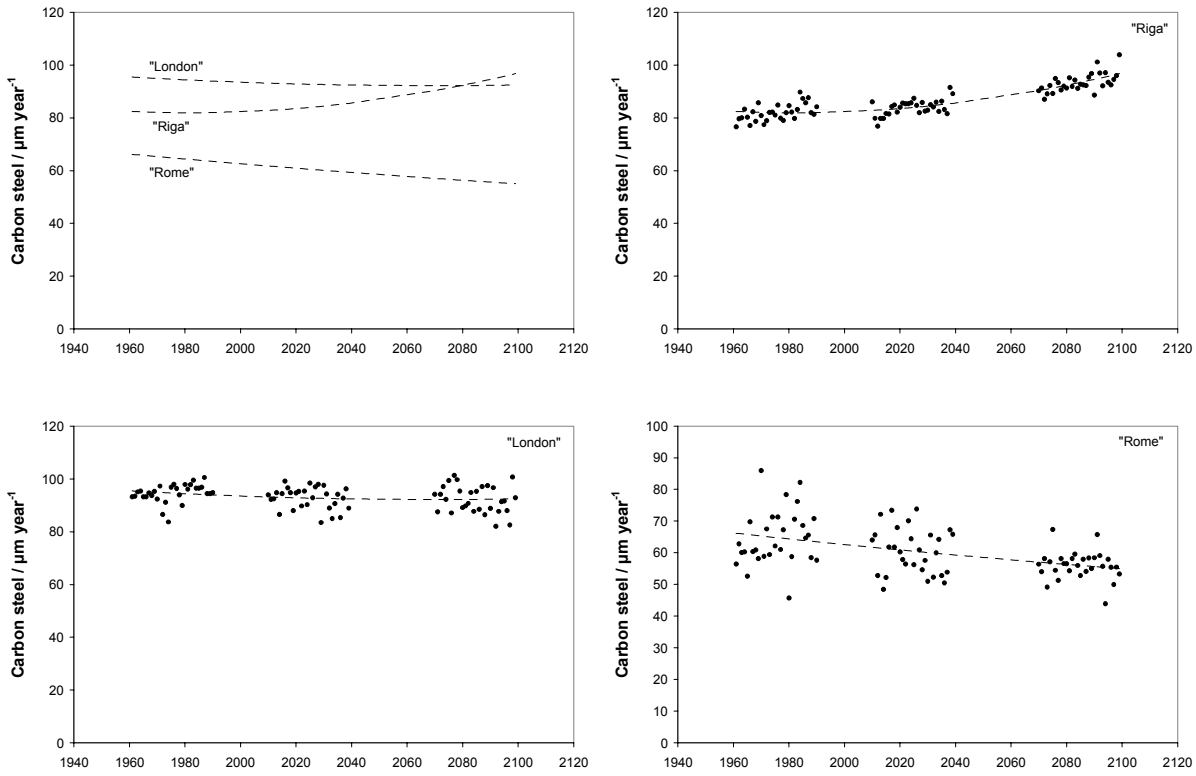

Figure 3.2.6. Calculated corrosion of carbon steel due to chloride deposition assuming a constant chloride deposition of 300 mg m^{-2} day^{-1}. Results for three grid cells are given, in which the cities of Riga, London and Rome are located. The upper left figure shows all fitted lines for ease of comparison.

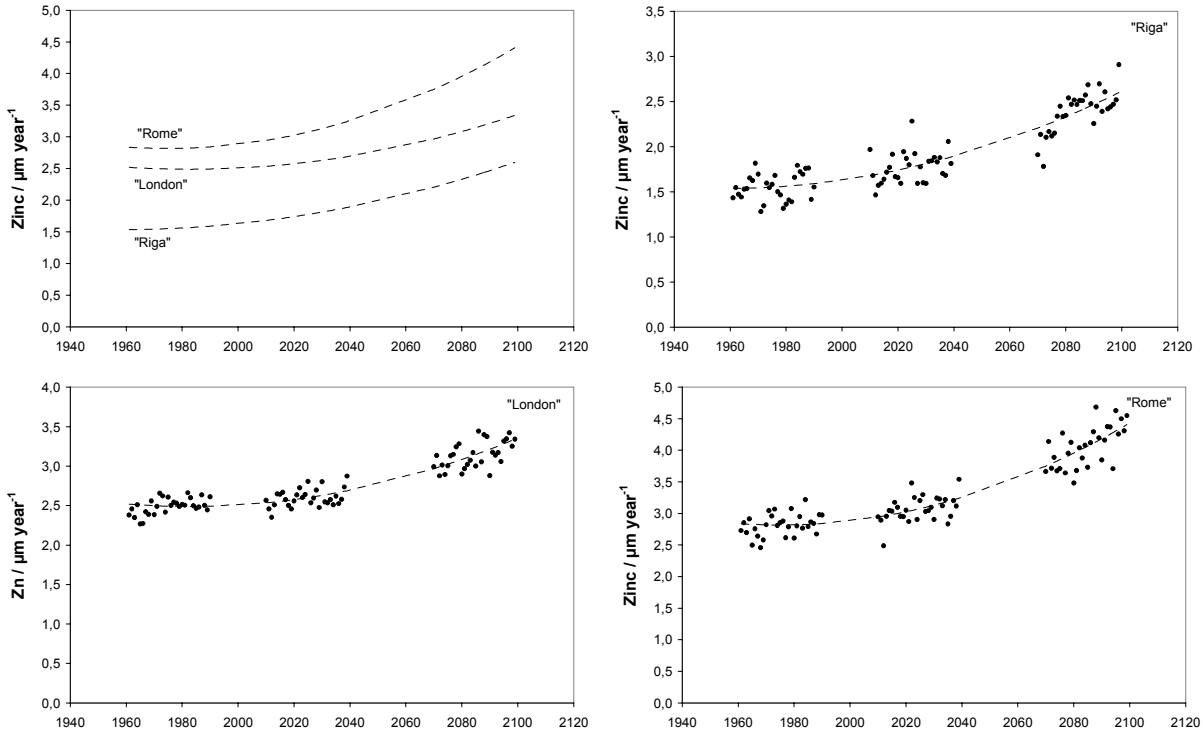

Figure 3.2.7. Calculated corrosion of zinc due to chloride deposition assuming a constant chloride deposition of 300 mg m^{-2} day^{-1}. Results for three grid cells are given, in which the cities of Riga, London and Rome are located. The upper left figure shows all fitted lines for ease of comparison.

3.3 Wood

Attack by fungi is the principal mechanism by which wood deteriorates in open-air constructions. The new improved index of climate risk to wood, developed within the current project specifically for the cultural heritage field, took into account the real moisture penetration depth, and resulting real infestation volumes, and time when the moisture content was above the critical level at which the fungal growth appeared, 20% in the present calculations. Furthermore, the rate of the decay by fungi was assumed proportional to the number of degrees by which the temperature exceeds 2. The final form of the Climate Risk Index for Cultural Heritage (CRI_{CH}) was therefore:

$$CRI_{CH} = \sum_{Jan.}^{Dec.} (T-2) \int_0^{D_{\max}} t_{crit}(D)\ \sigma(D)\ dD$$

where : T is the mean monthly temperature in ^{o}C, $t_{crit}(D)$ is monthly time when moisture content in the $\sigma(D)$ percent of the wood's cross-section at distance D from the external wood surface exceeds the critical level, D_{max} is the maximum distance at which infiltration of water produces moisture contents above the critical level. D_{max} is specific for each species of wood and is determined experimentally.

For the sake of present calculations which were done for quarterly time intervals this formula was modified to:

$$CRI_{CH}^{Q} = (T_Q - 2) \int_0^{D_{\max}} t_{Qcrit}(D)\ \sigma(D)\ dD$$

where: TQ is the mean quarterly temperature and tQcrit is quarterly time when moisture content at D exceeds the critical level. Otherwise the symbols are the same as for the formula above.

The risk indices were determined for fir and oak. As fir proved slightly more susceptible to fungal attack, risk values and changes are given below for fir. The index is obviously sensitive to precipitation pattern which controls the time wetness of the exposed surface of wood and infiltration periods. The realistic precipitation patterns were obtained in the same way as described in chapter 3.1.5. on damage of clay containing sandstone. The only difference consisted in finding the worst case scenario by selecting such combinations of rainy days that maximized the risk index.

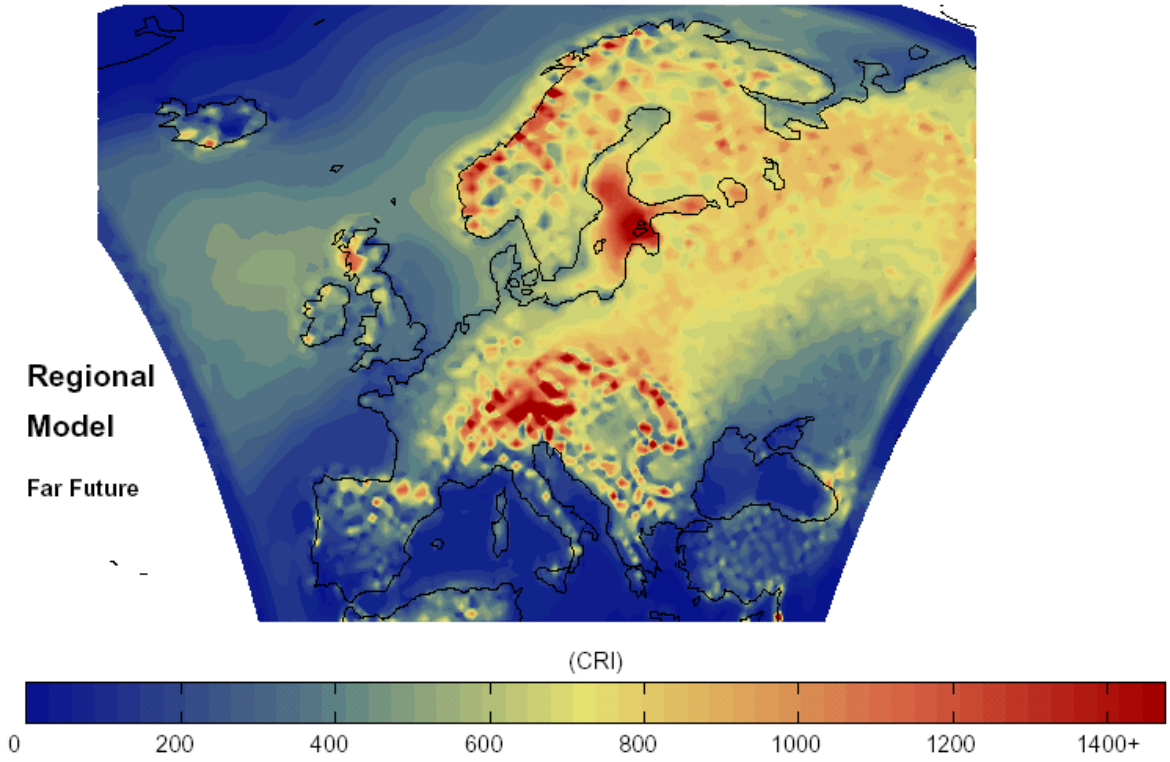

Figure 3.3.1. Climate risk index CRI_{CH}^{Q} mapped over Europe excluding seas.

As one can see from Figure 3.3.1, the risk to wooden structures exposed to the outdoor conditions will be especially high in Norway and in the mountains mainly because of high precipitation. In contrast the drier southern Europe will be not affected by the fungal growth significantly.

A similar tendency is visible in the maps which show change in risk of wood destroying fungi (Figure 3.3.2). An increase of up to 100% will afflict Scandinavia and Northern Russia, whereas Western and Southern Europe will experience a decrease in risk.

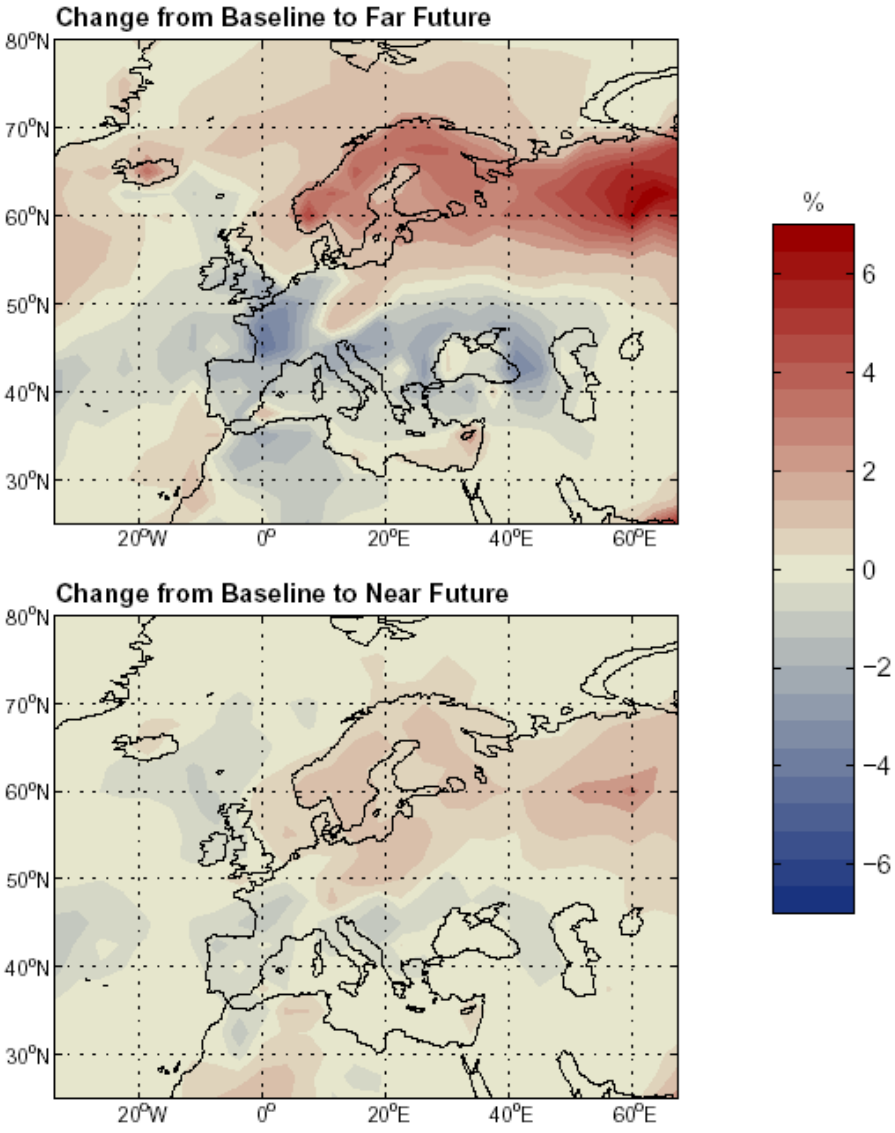

Figure 3.1.13. Calculated change in the risk of wood deterioration due to the fungal growth.

3.4 Glass

In the MULTI-ASSESS project a separate statistical analysis has been performed for glass of medieval composition, i.e. high concentration of network modifiers i.a. K_2O and Na_2O and use of K_2O instead of Na_2O. Two glasses have been evaluated, (M1) and a less sensitive (M3).

The analysis has resulted in a simplified dose-response function for M1, a more sensitive glass with higher K_2O content

$$d(K) = -0.28 + 0.028Rh - 0.055T$$

where d(K) is the depth of the leached layer with respect to K in µm and the constant is depending on the pollution situation and here valid for an SO_2 concentration of 10 µg m^{-3} and an NO_2 concentration of 60 µg m^{-3}.

A comparison between the near future (2010-2039) scenario and the baseline (1961-1990) scenario results in changes in d(K) from -0.3 to +0.1 µm while a comparison between the far future scenario (2070-2099) and the baseline scenario results in changes in d(K) from -0.7 to +0.1 µm. In other words, the glass corrosion decreases or remains unchanged depending on the geographical location (figure 3.4.1)

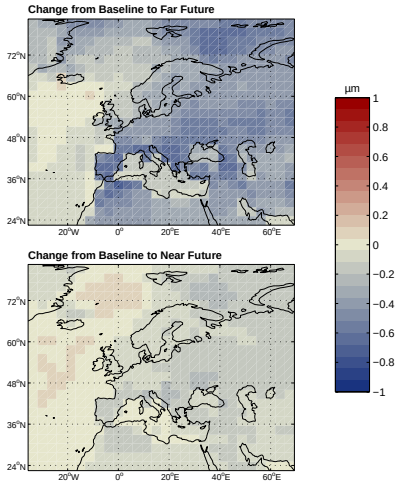

Figure 3.4.1. Calculated corrosion of glass M1 with composition representative of medieval stained glass windows measured as the depth of the leached layer with respect to K content.

3.5 Soiling and blackening

In recent times there has been a shift away from the high levels of sulfate deposition. Now deposits are dominated by diesel soot and nitrogen compounds. This means that crusts found on buildings in the future may show a more pronounced organic chemistry. The oxidation of deposited organic material can change the colour of building surfaces. The decrease of soot concentrations in urban areas can also lead to a self-cleaning of historic buildings by rain and wind (e.g. Davidson et al. 2000).

Aesthetic damage

The decreasing concentrations of acidic pollutants over the past decades mean less reaction and chemical damage to stone surfaces. This increases the significance of the blackening and has raised the importance of aesthetic considerations.

Soiling or blackening of building materials is a visual nuisance resulting from the darkening of exposed surfaces by the accumulation of particulate matter (Haynie, 1986). It is related to the surface area covered by carbonaceous fine particles, which contain dark elemental carbon. Consequently, the deposition of urban particulate matter onto the surfaces of buildings has long been a cause of concern. The poet Horace was especially annoyed by blackening of religious buildings in Ancient Rome (Brimblecombe, 2000). By the mid 1600's, those concerned with the appearance and beauty of architecture, such as the diarist John Evelyn, were particularly worried about the ugliness of London's soot encrusted buildings. The carbonaceous deposits are retained on surfaces and have high optical absorptivity (Lanting, 1986), so are very effective at blackening building surfaces.

During the second half of the 20th century blackening remained an important issue (Newby et al. 1991). As the use of coal in many cities has declined dramatically, diesel soot has become the significant source of elemental carbon. Despite continued concern, in some locations decreasing atmospheric soot concentrations have meant that in recent years there has been less darkening and in some cases rainfall removal has made buildings much cleaner (Davidson et al. 2000). Biological activity, perhaps supported by an ongoing increase in organic pollution, may also contribute significantly to stone blackening (Viles and Gorbushina, 2003).

Future change in the colour of building surfaces

The 21st century offers the potential for dramatic changes in the blackening patterns due to new climate regimes, most particularly through changes in wind driven rain. In today's urban environments, where it is likely particle concentrations will decrease, as a result of tightening legislation, urban historic buildings could self-clean, but may develop new patterns of darkening. Therefore future blackening patterns will be a balance between accumulation and redistribution: (1) the accumulation will be mostly influenced by atmospheric elemental carbon concentrations, surface roughness and time of wetness; (2) the redistribution will be dominated by wind driven rain, precipitation amount and wind direction. A seasonal rainfall increase may also encourage micro-organisms growths which themselves can produce widespread blackening (Viles 2002).

Moreover, today and near future cleaner atmospheres, but perhaps more dominated by organic pollutants a yellowing process may be of greater concern (Grossi et al. 2006b). Urban atmospheric deposits richer in oily organics and poorer in elemental carbon are liable to produce brownish-yellowish coatings on urban building stones increasingly noticed in places like the Tower of

London. The oxidation of soot on the surfaces of crusts can produce HULIS which has a brownish colour.

The changing forms of blackening can be traced with the use of historical photographs and there are possibilities of predicting future changes from fluid dynamics, although this largely lies outside the scope of NOAH. Some initial work on the Norwich Cathedral of St. John is shown in Fig. 3.5.1.

Figure 3.5.1. Blackening patterns on Norwich Cathedral of St. John ascertained from photographs in the 1920's (red) and the extension of soiling by 1960 (green).

Project
no. SSPI-CT-2003-501837-NOAH'S ARK

NOAH'S ARK
GLOBAL CLIMATE CHANGE IMPACT ON BUILT HERITAGE AND CULTURAL LANDSCAPES

Instrument: STREP

Thematic Priority 1.2.1 POLICY-ORIENTED RESEARCH

Deliverable 7
"Scientific reference on mechanical damage and failures of historic structures due to weather effects and related natural disasters and their mitigation strategies and measures"

Due date of deliverable: May 2006
Actual submission date: June 2006 (Softcopy)) - July 2006 (Hardcopy)

Start date of project: June 2004 Duration: 3 years

Lead Partner:
Institute of Theoretical and Applied mechanics of the Academy of Sciences of the Czech Republic – ARCCHIP Centre of Excellence
Contributing Partners:
ISAC Bologna (Italy)
UEA Norwich (UK)

Project co-funded by the European Commission within the Sixth Framework Programme (2002-2006)		
Dissemination Level		
PU	Public	X
PP	Restricted to other programme participants (including the Commission Services)	
RE	Restricted to a group specified by the consortium (including the Commission Services)	
CO	Confidential, only for members of the consortium (including the Commission Services)	

Deliverable 7: Scientific reference on mechanical damage and failures of historic structures due to weather effects and related natural disasters and their mitigation strategies and measures

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Jiří Bláha, Jan Bryscejn, Ivo Herle, David Mašín, Stanislav Pospíšil, Zuzana Slížková

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2. Deteriorating action of weather and related natural disasters
3. Review of typical mechanical damages and failures of historic objects
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6. Physical behaviour of architectural heritage in special weather situations – experimental investigation on models
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1. Introduction and objectives

The sensitivity of historic structures and elements to weather and disasters has been studied using records of damage and failures gathered in literature and special databases. It should be emphasized that any historic structure or element cannot be dealt with unless its material characteristics and a general environmental situation, (e.g. hydrogeological conditions), have been taken into account, which is reflected in the ranking results and mitigation strategies, too.

This report presents selected examples from a developed information system containing data on typical damage and failures related to weathering effects and disasters action, namely wind, floods and landslides.

Furthermore, in specific cases, not the historic structure but its surroundings and supporting structure are sensitive to climatic conditions, which can adversely affect their characteristics and cause damage to cultural heritage objects.

The applicability of preventive measures needs quantified information and therefore, special experimental methods have been developed and tested for possible use in further investigations and verification of expected measures. The relevant results of pilot tests as well as detailed planned experiments are shown in the report.

2. Deteriorating action of weather and related natural disasters

Weather effects can influence both the outdoor as well as indoor tangible cultural heritage. The individual components are usually listed as follows.

Radiation

Cultural heritage objects are mostly permanently exposed to the action of cosmic, solar and Earth radiation. Physically we distinguish between corpuscular (nuclear) or electromagnetic radiation, (divided according to different wavelengths into radio waves, heat radiation, infrared radiation, light, ultraviolet radiation, x-ray and gamma radiation). Specifically, objects directly exposed to solar radiation exhibit damage and failures due to heat and UV radiation or light. Here the ionic radiation, which is stronger from the point of view of energy, may cause chemical change in materials (e.g. netting or cleavage of polymers) on one hand, on the other hand the non-ionic radiation exhibits mostly thermal effects, (e.g. Desh 2002), see below.

Temperature

Temperature belongs among the worst climatic factors. In historic environments, it is shown by cyclical changes in a very broad band, which is dependent on the geographical position and the year. In Central Europe it falls into a range of about -25°C to about +30°C. For some technological monuments this interval can be several times higher. All building materials are sensitive to temperature, and they change their volume depending on temperature changes. This dilatation is positive (expansion) with the temperature increase and negative (shrinkage) with temperature decrease in the majority of building materials. The temperature effects and namely the temperature gradient action are usually underestimated in practice, even though they are known and published.

Water

Water acts on historic materials and structures in all phases of its state and it is their most harmful and dangerous enemy which can, together with temperature or other factors, cause deterioration to or even destroy a monument very quickly. Water acts in its solid phase as ice or snow, and in the fluid phase it attacks as rain, condensation or water trapped in depressions or voids, also as underground water which can moreover flow and carry corrosive substances or compounds. A possible erosion of soil under foundations represents another very dangerous phenomenon. In the gaseous state, the water increases the relative humidity of the air and creates conditions for the increase of moisture content of materials as well as for the life of biotic agents. Wet processes should be avoided or at least substantially reduced to the minimum necessary extent during restoration works.

Among the greater threats to building materials in historic structures are *cyclical changes of moisture content* in materials, namely in the case of a material containing soluble salts (crystallization and hydratation pressures generated at reversible changes of phases or crystal phases of salts) or clay materials (swelling of clay). In many cases, a relatively high but stable content of moisture in the building is less harmful than a fluctuating even lower moisture content. In some cases, drying of permanently humid materials may be very dangerous, (e.g. disintegration of marlstone due to a quick loss of freely bound water).

Air

Normal gases present in the air (oxygen, ozone, and carbon dioxide) react with some materials and may cause their degradation. The air composition cannot be changed, which limits possible preventive measures. In recent years the ozone content is increasing due to unfavourable factors caused by human impact, and this trend should be stopped.

Air pollutants

Gaseous pollutants in the air, mainly sulphur and nitrogen oxides, have similar effects as the air. Fluid pollution disperses in a shape of a cloud which contains aerosol, salts, and

acids and alkali soluble in water. The solid phase particles create an important component of the air pollution, e.g. sand, dust, soot, etc.

Wind

Wind primarily causes loading and mechanical damage of structures, nevertheless, it also increases or decreases the chemical action of water and gases on cultural heritage objects. The flow around monuments substantially influences the deposition of pollutants, biological colonisation, cycles of drying and wetting, as well as mechanical wear of the attacked surfaces. Wind transports water, salts, dust and gases to the object or building or can conduct them away.

Synergy of weather factors

Weather factors mostly act on monuments in a synergic way. The simultaneous action of temperature and water in repeated freezing/thawing cycles is a typical example of a situation very dangerous for wet porous brittle and quasi-brittle materials. The interacting influence of temperature and moisture causing repeated and uneven volumetric changes results in material deterioration and propagation of defects. In combination with abrasive particles, the wind can cause remarkable surface erosion, (e.g. on monuments in sandy deserts). However, they are numerous other examples, e.g. moisture and deposition mechanisms, wind + water + pollutants penetrating as weak acids into materials.

Unexpected events or disastrous events are not the most frequent causes of damage and failures, however, their consequences are mostly very harmful and catastrophic. Moreover, recently their more frequent occurrence is attributed to climate change and especially the influence of global warming. Therefore, they are considered in more detail in the classification below.

Floods

Floods occur more and more in urbanized territories and have different forms from the extent and duration points of view. They cause damage and failures due to static and dynamic loads (water pressure, water flow, uplift forces), due to impacts of floating objects, due to wetting of building materials, (which is difficult to remove) and due to a possibility to transfer chemical pollutants and biological infection. Even though any flood is usually a short event, the repair of consequences and results require a very long time and enormous effort.

Earthquake

Seismic activity threatens thousands of cultural heritage objects. Not only natural seismicity generates dangerous vibrations and displacements, but also man made seismicity, so called “industrial or technical” seismicity, proved to cause severe damages, mostly on masonry. It can be generated as technological due to quarry blasting, transportation vibrations and shocks (e.g. supersonic aircrafts) and microseismicity in mining areas. Earthquake problems are not considered in this report.

Landslides

Landslides and similar phenomenon (e.g. avalanches) cause major loss of historic objects and the architectural heritage. They affect large areas and the damage is mostly irreparable, in contradiction to earthquake damage. The object or building is dislocated away from its original position and in many cases is partly overturned.

Strong winds, storms, hurricanes

Strong winds and storms cause damage and failure in both the cultural and natural heritage. Windstorms are dangerous namely for tall buildings, high or light roofs, slender building elements and all objects in the vicinity of high trees.

Other natural catastrophes

Strong hail, snow and sandstorms can exhibit catastrophic features due to possible impacts, overloading, icing and other sudden effects.

Fire

Climate change with long dry periods increases the danger of fires. They were historically more dangerous in settlements than nowadays, however, every year there are still losses of important monuments due to fire. It can be started by lightning[1], short-circuits, human error or by arson.

Impacts of vehicles

This group of factors includes the impacts of vehicles, ships or aircrafts on a historic monument. Quite frequent impacts cause only superficial damages, namely on town or castle gates or bridge parapet walls. Bridges are further endangered by ships, ice blocks and floating objects during high water events.

[1] Electrical discharge itself is one of the usual weather factors and may cause also structural damage, besides the ignition, (see the Apendix).

3. Review of typical mechanical damages and failures of historic objects

3.1 Introductory comments

Analysis of failures of cultural heritage buildings and design of appropriate remedial or mitigation measures need a systematic study of damage mechanisms, damage manifestation and failure patterns. This can be effectively done only with the support of relevant and up-to-date databases, information systems and in some cases also special investigations utilizing methods of experimental structural and material research. The limited extent of the project cannot solve this problem in detail, therefore, only a suitable methodology has been developed.

The lifespan and serviceability of materials, elements, buildings and ensembles of architectural heritage are influenced by various factors, including to which type of action they are subjected. A great deal of attention is devoted to those which affect the physical existence of the object or building. Nevertheless, almost all intangible heritage features and values, especially historic cities, can be severely damaged, which is definitely a defect and can even attain the dimension of a failure. We can divide the aforementioned factors causing the deterioration of the physical state of monuments into three categories according to the period of their action: i) before the production of the object or building, ii) during the production/construction phase and iii) during the service life of the object or building, (Drdácký 2001). Even though historic buildings exhibit numerous defects and failures caused by factors originating before their construction, which is an important issue for conservation theories and approach definitions, the third aforementioned category is the most important one for architectural heritage, and it can be divided into the following groups: weathering effects, biological factors, incompatibility, loads, operation, concept, design, materialization and alterations to the building or object, unexpected events & "injuries". Climate change influences or acts in synergy with all the aforementioned factors which are summarised as follows.

Weathering effects

Weathering effects involve namely action of radiation, heat, water, air, wind and air pollutants. They affect cultural heritage mostly in a synergic way and occur in both the exterior and the interior spaces. They have already been described.

Biological factors

The influence of biological factors has been widely studied and it encompasses microorganisms, plants and animals attacking historic materials and causing their deterioration and failure. They include fungi, moulds, bacteria, lichens, mosses and algae, plants, insects, birds, sea creatures, reptiles and mammals especially man, who represents one of the most dangerous threats to cultural heritage.

Incompatibility

Most technical materials, namely building materials, elements and structures are created as non-homogeneous composite systems, which combine materials of different physical, chemical and biological characteristics. They respond to the acting loads and influences differently, and when a common threshold of tolerance is surpassed a defect or failure occurs. In the case of architectural heritage, the intangible values are to be taken into account, too. In practice we distinguish between at least the following types of such an incompatibility: physical, chemical, biological, architectural (including aesthetic) and social.

Loads

Historic buildings are subjected to various loads that we usually describe as static, periodic (repeated or dynamic) and movement of supports. The resulting stresses are caused by exterior forces, (e.g. gravitation, pressure, uplift forces, inertia forces), which can have different directions, intensity and duration, and by deformations, (e.g. induced: temperature or

moisture difference dilatation, subsoil movement, vibrations or from internal material characteristics: creep, shrinkage, crystallization). They cause local material damage and failure by shear, tension, compression or fatigue (mechanical as well as environmental).

Operation

Use of monuments brings about numerous degradation factors, first of all, wear, which gradually exhausts the lifespan of the object or building. Wear and threat of failure increase with inappropriate use of cultural heritage buildings, which can act mechanically (overloading) or in the area of building physics (unsuitable change of interior climate, creation of diffusion barriers). On the other hand, the operational danger is reduced by means of regular and timely maintenance, which is one of the most important safeguarding factors.

Concept, design, construction of and alterations to the building or object

The initial concept, design and construction of the object or building influence its lifespan most significantly. An inappropriate choice of construction site, water retention, snow or pollutants, wrong details, insufficient insulation, insufficient ventilation and non-suitable materials or technologies can decrease substantially the life of a historic building. We consider such a work defective or even a failure. However, such a flawed concept, design or materialization of a monument in the field of conservation is barely rectified, because such attributes are sometimes understood as a part of cultural heritage which should be conserved. The authors do not agree with such an approach and support conservation approaches which in an acceptable way and after proper documentation improve the building to prolong its life and safeguard its original parts. In any case, the conceptual errors are frequently associated with restoration works and similar changes made to historic objects and buildings.

Unexpected events & "injuries"

Unexpected events do not represent the most frequent cause of damage and failures, nevertheless, their consequences are mostly catastrophic and disastrous, therefore this contribution is more focused on them. They involve floods, earthquake, landslides, avalanches, strong winds, windstorms, hurricanes, and fires, but also man made disasters, e.g. wars, vandalism, explosions, impacts of all kinds of vehicles or floating objects etc.

3.2 Literature survey of historic cases of damage and failures

Most data on damage and failures are not published in widely accessible publications. They are mostly hidden in case study reports or failure analysis reports, frequently written in language which is not commonly understandable, (e.g. Adamcová et al, 2004). Therefore, a database of damages of historical materials and structures has been developed and its pilot version is presented in the Annex 2.

A detailed review of records concerning damage and failures generated by strong winds, storms or hurricanes has been produced for the Czech regions. The results are presented in the Annex 1. The damages of wind action on built and natural environments are recorded by the European Environmental Agency and published.

Similarly, the history of flood damages on Charles Bridge in Prague shows that this medieval structure suffered severely from quite frequent and heavy floods. The typical damages from flood on architectural heritage are presented in Annex 2, too. Numerous papers deal with historical cases referring back to the 16th Century, (e.g. Munzar, Ondráček, 2005 or Deutsch, Pörtge, 2001). Specific methodology for flood damage assessment of cultural heritage properties has been suggested by Kelly, 1994. Mattsson and Oftedal studied the post flood biodeterioration of cultural heritage in Norway. Flood risks are subject of a 6th FP project FLOODsite.

Landslides in the Czech lands have been evaluated and the results are presented in detail in the Annex 1. In some European countries, there are quite large regions which are prone to landslides , e.g. Bulgaria, Italy, Slovenia, Scandinavia or the Alps. The landslide risks have been investigated in an integrated project LESSLOSS, supported from the EC 6th FP.

3.3 Damage and failures

The arrangement and classification of damage and failures can exploit different points of view, because of their vast variety. Let us briefly mention some of the classification approaches. Failures are usually sorted according to their *consequence* (defects, relevant damages, failures), according to materials or structures made from these materials. In the architectural heritage field we distinguish between failures of stone, stabilised clay, burnt clay, mortars and plasters, concrete, wood, metals and plastics. Another possibility takes advantage of building typology, e.g. houses, buildings, halls, towers, tanks, bridges, roads and railways, sculptural works, etc. In buildings we frequently use the classification of structural typology or structural function, sometimes with the incorrect terms – bearing and non-bearing structures, (which neglects the fact that any structure has been created to sustain some loads or action, therefore as the "bearing" one).

In this report, we accepted the sorting of damage and failures according to their manifestation, their relation to the selected causes of damage and failures and to possible preventive measures which are dependent on structural typology and especially on the material used.

All abovementioned criteria are very important characteristics of damage and failures and, therefore, they should be recorded in the relevant databases. There might be terminological problems because there is no widely accepted system for classifying damage and failures of monuments. In such a case it is useful to use terminology developed and introduced for other purposes, e.g. listing of cultural heritage.

A very detailed system for damage diagnosis on stone monuments has been developed by Fitzner and Heinrichs 2002, who classify weathering forms into four levels with four groups of weathering forms, 25 main weathering forms, 75 individual weathering forms and usually six different weathering intensities. Such a system is based on study of damage and failures from the material point of view. Similarly, a more practical system has been suggested by Smith, Whalley and Magee 1992. However, this report is rather focused on structural and architectural features and, therefore, too complex classification systems cannot be reasonably used.

3.3.1 Damage and failure features on historic materials and structures

3.3.1.1 A note on mechanism of material damage

Even though this report is not primarily focused on material damage assessment, it is useful to remember that "sound" material is a necessary condition for physical existence and sustainability of architectural cultural heritage. Knowledge of basic damaging mechanisms of historic materials is indispensable for their appropriate and effective protection and safeguarding. In principle, the historic materials are deteriorated by means of three mechanisms which in many cases act simultaneously or which at least interact together, simultaneously or in time sequence.

Physical damaging

Material deteriorates mainly mechanically due to the action of external forces (from loads, movement, impacts, human action, etc.) or internal forces, (e.g. generated by forced deformations at uneven temperature and moisture changes). The time factor may be important for some materials, e.g. long term overloading of timber. Further, erosion problems decreasing cross-sectional characteristics belong to this group, too. Physical damage typically results in a mechanical breakdown, for stone typical examples see in Smith et al. 1992.

Chemical damaging

The material is chemically attacked by reactive compounds present in the surrounding environment or produced by biological agents. In the second case we distinguish between assimilation and dissimilation damaging. In the former case, the material serves as a nutrition source for parasite organisms that e.g. decompose cellulose in organic materials. In the latter case, products released from colonised organisms without nutrition aims cause deterioration. Chemical damaging can be initiated or accelerated by means of physical factors, e.g. temperature or light, (or another radiation), and then we speak about thermal damaging (well known for timber and marble) or photochemical damaging. In this category we can include also fire damage, even though in this case for some materials the physical damage may be dominant. Chemical damage results in solution and alteration, for examples stone Smith et al. 1992.

Soiling

Soiling is a general phenomenon which decreases the serviceability of historic structures and elements. It may generate only aesthetical defects but also more serious failures, e.g. reduction of pipe profiles, bridging of electrical circuits by mycelium, creation of a dark crust causing further increased surface heating and elevated temperature stresses. The material is here frequently only a carrier of the undesired layer which might initiate or accelerate the above mentioned degradation types. Soiling can be detected by alterations, deposition and biological colonisation.

3.3.1.2 Typical damage categories and manifestation

When classifying damage and failures we usually distinguish among:

- No damage or failure
- Destruction, total collapse or failure of a part of an object/building
- Relative displacement or rotation of a part of the whole object
- Deformations – elastic or irreversible (deflection, buckling, compression, …)
- Cracks in structures (including detachment and delaminations)
- Loss of material (corrosion, woodworm, …)
- Material disintegration (life time exhausted, alteration, ...)
- Moisture (capillary, leakage, condensation, hygroscopic, ...)
- Biological attack
- Material or structural heterogeneity
- Appearance changes (efflorescence, discoloration, structural change, soiling, …)
- Alterations (porosity change, salts, wrong changes, …)

The above-mentioned categories are very rough and in some cases overlapping. For practical use they are more structured and refined, and completed with typical samples etc. As it has been already mentioned, the most elaborate approaches are known from the field of stone damage assessment (Fitzner, Heinrichs 2002, Smith et al. 1992) and corrosion of metals. The stone deterioration is very closely related to climate effects, which can be seen in the Annex 2, and therefore, the ranking of structures and elements reflects this fact.

3.3.2 Causes of damage and failures of historic materials and structures

Determination of causes of damage and failures is the main aim of the failure analysis. On the basis of failure analysis preventive measures can be developed and applied. From such an analysis we know that most failures have not only one cause but they are a result of combinations of unfavourable conditions. Only about one third of failures might be attributed to one cause only. The other two thirds have statistically on average about 2.5 reasons, but in some cases failures have 7-8 causes (Drdácký 1991-1993, Drdácký, Kratěna 2000).

Selected cases of damage and failures, presented in the Annexes, are only illustrative examples which do not involve all possible causes, situations, materials and structures.

4. Ranking of structures, elements and situations according to their sensitivity to the weather and disaster effects

4.1 Wind effects

In the past the serious damage to buildings caused by climatic reasons – windstorms, hurricanes or floods – definitely belonged among the most remarkable events to be noted in chronicles and other written sources. Together with large fires, often started by thunderstorms, they make the numerous groups of records in chronicles. As the actual results of historical research shows, the windstorm damages of roofs were recorded relatively often in the past, (see Annex 1). We can understand that the damage descriptions might have been exaggerated and sometimes even overestimated on purpose to obtain funding for repairs more easily. On the other hand the detailed and reliable descriptions of particular incidents are very valuable for defining the weak points of typical building structures.

Churches with their high roofs and in particular steep spires represent the largest group of buildings mentioned in written sources. Outlook towers with timber structures on the tops of the hills and standing for the most part separately from the traditional settlements were maybe the most endangered building type, especially around the 1900. Quite surprising is the report from 1842, which speaks about the menhir in Klobuky (Central Bohemia) falling to the ground due to a hurricane. To this category we include also the failure of freestanding walls, as e.g. attic gables, ruins, fencing walls etc.

Most of the damage caused by strong winds touched the roof covering. Wooden shingles were in this sense much more resistant than for example ceramic or slate tiles. Copper sheets when used in pitched roofs of a larger extent caused serious problems too.

The total collapse of an all-timber structure of a roof spire was generally not the result of structural faults in timber construction but was connected with longer established existing problems, as for example rotten wall plates or roof leakage. That means that the periodic monitoring of wood condition within the constructions is essential to prevent future damages. A combination with other structural failures – cracking in masonry or vaulting – could be very dangerous leading to a collapse of the building as a whole.

Generally, the movement of the air around buildings influences initiation and development of damage due to its motion, too. However, this effect must be treated rather in the weathering group of problems.

Ranking of structures and elements vulnerable to wind effects

W0 Wind resistant structures and elements

W1 Vibration prone elements and structures

- windows and window glazing
- architectural elements (e.g. pinnacles)

W2 Wind releasable elements

- roof covering

W3 Structure susceptible to partial damage by wind

- roofs
- windmills
- tall sculptural works

W4 Structures and elements vulnerable to overall collapse due to wind action

- Free standing walls and elements (attic gables, ruin walls, fencing walls, chimneys, menhirs, poles, etc.)
- Light and tall buildings (towers, timber houses, etc.)
- Trees

4.2 Landslides

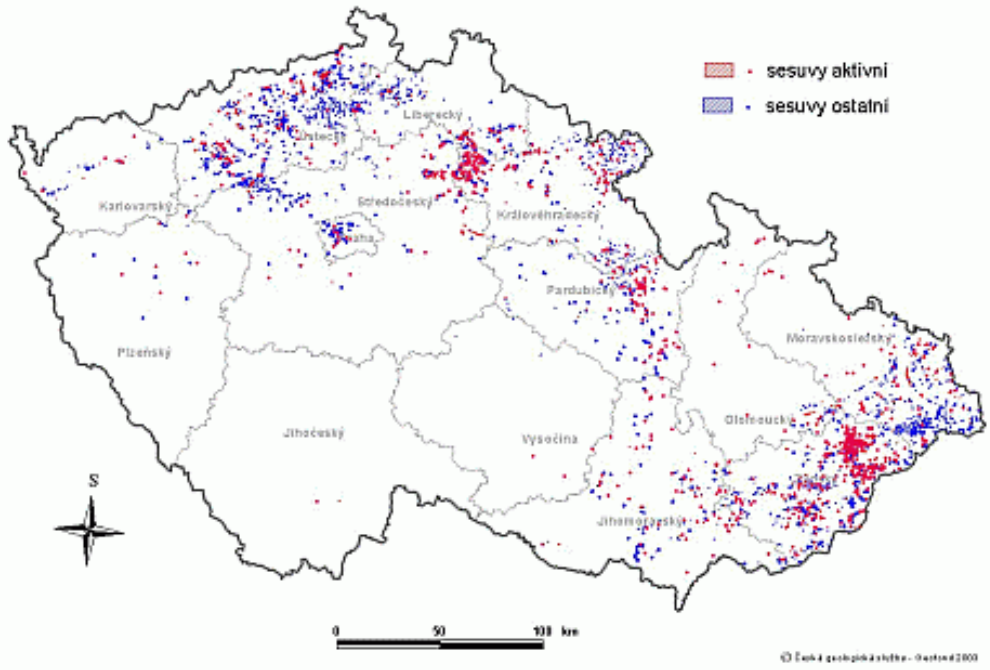
Landslide event is usually caused by a combination of different factors, the most important are:

Material properties of soil/rock massif In general, more susceptible to failure are fine-grained soils which are characterised by significantly lower friction angles (Φ) compared to coarse grained materials (the typical critical state friction angle of clay is of the order of 22°, whereas of sands it is 35°). Friction angle of clays further reduces in the case of previous deformation (pre-existing slip surface, stabilised old landslide) up to the residual value of approx. 6°. In theory, the critical state friction angle Φ is related to the "angle of repose" of the soil (α), an inclination of the slope under stable conditions. In dry homogeneous material $\alpha=\phi$, in water saturated state with ground water table on the surface $\alpha=\phi/2$.

Geological composition. The stability of the slope may be further reduced by unfavourable geological conditions. A typical unfavourable example is flysh material, with interchanging layers of sandstone and clay stone. During rainfall the sandstone layer quickly saturates due to high permeability, which causes decrease of effective mean stress in the impermeable layer of clay stone, which is than susceptible to failure. Another example of geological conditions pre-defining slope collapse is a rigid rock stratum lying on a highly plastic fine grained material. Rigid blocks load a slope which fails in the case of high precipitation.

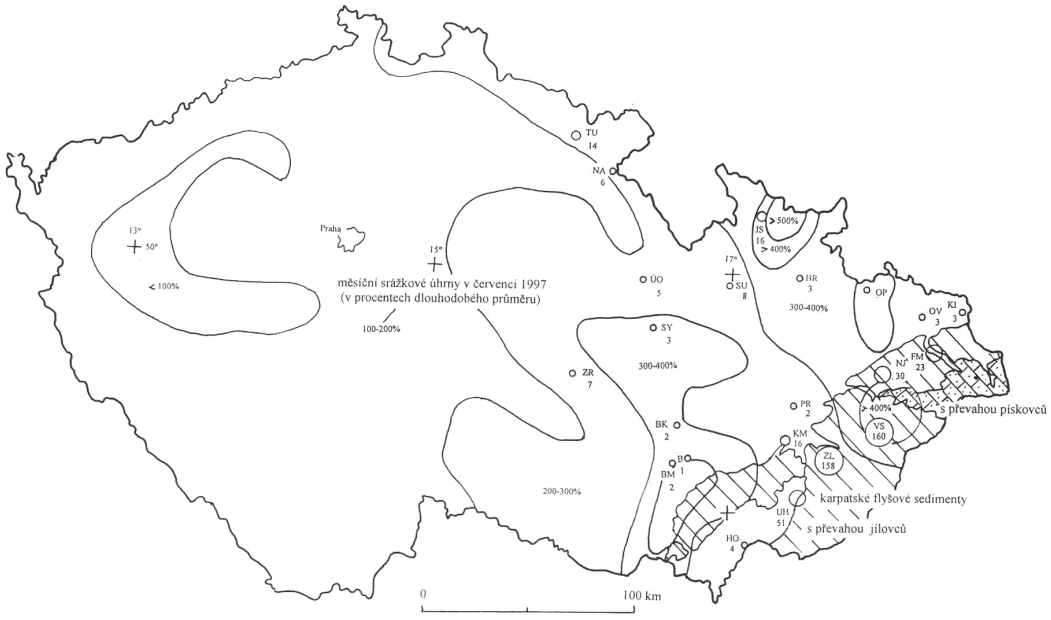
Precipitation, water saturation. It is one of the most important aspect causing landslides. Increasing of water table causes an increase in pore pressure. According to Terzaghi's principle of effective stresses, increase in pore pressure causes decrease of the mean stress p, while the shear stress q remains unchanged (water can not sustain shear stresses). Consequently, stress state moves towards Coulomb's failure envelope (defined by a friction angle Φ) which may lead to slope failure.

More problematic from the point of view of landslide hazard is an extreme climatic event (strong rainfalls, quick snow-melting in spring) which causes sudden increase of the pore pressure and may be reason for reaching Coulomb's failure criterion. Annual average changes are less important.



As an illustration, Figure 4.1 shows distribution of landslide events in the Czech Republic. Red dots denote active landslides, whereas blue dots stabilised landslides.

Figure 4.1 may be compared with Fig. 4.2, which shows the amount of precipitation in July 1997 by means of percentage of monthly long-term average (see 400% in south-east Czech Republic). The majority of active (red) landslides in the south-east part of the Czech Republic have been initiated during a single extreme precipitation event combined with unfavourable geological conditions (flysh material).



Obr. 1 Přehledná mapa České republiky s měsíčními srážkovými úhrny a s počtem sesuvů nahlášených do poloviny srpna 1997 v jednotlivých okresech

Figure 4. Cause of the landslides in Moravia in July 1997: A map showing the amount of precipitation by means of percentage of monthly long-term average (see 400% in south-east Czech Republic).

Slope inclination An important factor influencing susceptibility of the slope to failure. In general, slopes with medium inclination (15°-30°) are the most problematic. Slopes with a smaller inclination are usually stable due to small shear stresses acting in the ground (with the exception of slopes with pre-existing slip surfaces, where residual friction angle has been reached, see "material properties"). On the other hand, it turns out statistically that slopes with higher inclination than about 35° are usually also stable. If such a slope was susceptible to failure, it would have already failed in the geological history. Slopes with high inclination are often made up from rigid rocks, where other types of instabilities, such as rock falls, may be expected.

Technical disturbance of the slope. It is an important factor which may be influenced by taking correct protective measures. The probability of failure is increased by cuts (unloading) in the slope toe and loading of the crest, insufficient water drainage which causes infiltration of water and increase of pore pressures, retaining wall without sufficient drainage, etc.

In the case of landslides, the structures and elements are not ranked, because it does not make sense to do this. On the other hand, the dangerous situations should be ranked, which has been generally described above and can be summarized as follows:

Ranking of geological situations prone to landslides

G0 Landslide proof geotechnical conditions
G1 Areas under landslide prone situations (threaten by the flow)
G2 Landslide prone slopes – generally the angle between 15° and 35°
G3 Landslide highly prone soils
G4 Landslide susceptible geotechnical conditions

- Natural (layers, ..)
- Man made errors

4.3 Floods

Historic materials, structures and territories (landscape, gardens etc.) are subjected to unusual loads and actions. First of all, we have to have in mind that the law of Archimedes is valid and therefore all flooded objects are uplifted and some can even flow away from their original position, even inside interiors, where streams can occur, too. Naturally, static and dynamic pressures can destroy structures as well as trees and this phenomenon may be multiplied with the impact of floating objects or the creation of barriers from the floating objects or erosion of subsoil under foundations. Wet materials and structures are mostly losing their strength and stiffness characteristics and they exhibit substantial volumetric changes. Besides the mechanical action, during and especially after floods substantial chemical attacks are present also, mostly due to water pollution and salt efflorescence during drying processes. Therefore, the general ranking of structures and elements according to their sensitivity to flood is much more difficult than in any other situation. Generally, many effects occur after the flood as, e.g. compacting of infill, which can cause failure of partition walls, buckles of floors as a consequence of the uplift forces, cracks in vaults due to uneven settlement after the flood and many others.

Ranking of structures and elements according to their sensitivity to flood

F0 Flood resistant structures
F1 Structures from materials with a high moisture volumetric change

- Timber structures and elements
- Combined structures from different moisture expansion materials
- Some soils

F2 Structures from materials of strength highly degrading due to moisture

- Dried brick (adobe) masonry
- Masonry with clay (low lime or cement contents) mortars
- Decayed timber structures and elements
- Infill subsoil and fine particle subsoil

F3 Structures susceptible to partial damage due to flood

- Timber parts prone to uplifting and floating away
- Large bridges
- Pavements

F4 Structures and elements vulnerable to overall collapse or displacement due to flood

- Small bridges and walkways
- Free standing walls
- Light improperly anchored objects (summer-houses, etc.)

4.4 Weather effects

Taking into account the sensitivity of structures and elements to weather effects regardless materials from which they are created, we logically sort the structures according to their exposure conditions and morphological characteristics which influence water retention

or the eddies and flows around the monuments. The last item is reflected in the robustness categories in which material types are also mentioned.

Ranking of structures and elements vulnerable to weather effects

Sculpture and building surfaces ***exposed to rain*** are divided into five categories:

R0 Sheltered from rain

R1 Partly exposed to rain or/and moderate rain water runoff

- Vertical surfaces moderately exposed to winds

R2 Exposed to rain or/and heavy rain water runoff

- Roofs
- Inclined surfaces of sculptures
- Vertical surfaces exposed to prevailing and strong winds

R3 Complex shapes with horizontal surfaces

- Cornices
- Balconies
- Decorative architectural elements

R4 Complex shapes with water traps

- Roof and façade details

Structures and elements exposed to threat of ***rising dampness*** are classified as:

D0 Natural moisture contents

D1 Occasional moisture occurrence

- Walls which are damp due to splattered water (bridge parapet walls, ..)
- Structures occasionally affected by an elevated water table

D2 Permanent moisture contents

- Masonry highly contamined with hygroscopic salts or materials
- Masonry covered with damproof layers

D3 Permanent high moisture contents

- Buildings in lagoons
- Cellars or caves

D4 Cyclical alterations under water/open air

- Bridge piers
- Watermills
- Marine structures

Structures and elements ***exposed to sunshine*** (heat and light effects):

S0 Sheltered against light

S1 Sheltered against direct sunshine

S2 Partly exposed to sunshine

- Buildings in shadow of trees

S3 Fully exposed to sunshine

- South-east oriented façade

S4 Fully exposed to sunshine with elevated heat exchange

- South + SW +W oriented facades or roofs
- Flat roofs and pavement

Robustness (***volume of mass, detailing and material***) of the element or structure:

M0 Robustly resistant to weather effects

M1 Robust in form, sensitive material

- Porous materials
- Materials with low freeze/thaw resistance
- Water soluble materials

- Corrosion prone materials (alterations, crust creation)

M2 Resistant material, sensitive details

- Details with notches (stress concentration, manufacturing defects, ..)

M3 Form prone to uneven strains and gradients

- Edges, corners, protuberances
- Subtle elements fixed to massive parts

M4 Sensitive material & sensitive details

Weather effects represent one of the most deteriorating agents to cultural heritage, namely architectural heritage. It is beyond the scope of this report to deal with in detail with all possible strategies and measures mitigating these effects. They are listed here in order to emphasize the importance of detailed studies of combined weathering effects which increase the deterioration and call for specific preventive measures.

ANNEX 3

Letters of agreement and adhesion to the MACH proposal

- *Provincia Regionale di Siracusa, Italy*
- *Soprintendenza Regionale della Calabria, Italy*
- *Opera del Duomo, Firenze,Italy*
- *Associazione delle Dimore Storiche Italiane, Sez. Toscana, Italy*
- *ETCP - Piattaforma Tecnologica Italiana delle Costruzioni – Area Patrimonio Culturale, Ancona Italy*
- *Monumentwatch FL, Anversa, Belgium*
- *Generalitat de Catalunya- Department de Cultura, Direcció General del Patrimoni Cultural, Barcelona, Spain*
- *Direccion Generales de Bellas Artes y Bienes Culturales, Direccion Patrimonio Historico, Madrid, Spain*
- *Asociación Española de Normalización y cerificatión – AENOR, Madrid, Spain*

PROVINCIA REGIONALE DI SIRACUSA
IX SETTORE
PIANIFICAZIONE TERRITORIALE E PROTEZIONE CIVILE

Prot. IX Settore n 1098 del 22/March/2007 allegati n

Oggetto: Project MACH.

Provincia di Siracusa
Protocollo Generale
n. 0017881 del 26/03/2007
* 0 0 7 0 1 7 8 8 1 *

Al prof. ing. Giorgio Monti
Department of Structural Engineering
and Geotechnics
Sapienza Università di Roma
Via A. GRAMSCI, 53
00197 Roma (ITALY)

This is to confirm our interest in taking part in the project MACH as associate partner of the Sapienza Università di Roma, under your coordination.

We are proud of our historical city center of Ortigia being selected as joint case study of the project. We hereby confirm our availability in granting access to the buildings of our property located therein, jointly selected by the partnership, and to allow the placement of sensors and instruments foreseen in the project. We also ensure our participation to the scheduled coordination meetings and we are looking forward to the project outcomes.

Best regards

Il dirigente:
ing. Angelo DI PACE

Via MALTA, 106 96100 SIRACUSA – Codice Fiscale: 80001670894
tel. centralino: 0931/709111; tel. dirigente: 0931/480185; fax: 093122601
E-Mail: ingangelodipace@virgilio.it

Ministero per i Beni e le Attività Culturali
Direzione Regionale per i Beni Culturali e Paesaggistici della Calabria
SOPRINTENDENZA PER I BENI ARCHITETTONICI E PER IL PAESAGGIO PER LA CALABRIA

prot. 3488 A

28 MAR. 2007 Cosenza, March 28 2007

Al Dott. Piero TIANO
Coordinator
Istituto Per la Conservazione e
Valorizzazione dei Beni Culturali
Consiglio Nazionale delle Ricerche
Via Madonna del Piano
50019 SESTO FIORENTINO (FI)

Project **"MAINTENANCE OF THE CULTURAL HERITAGE CONSTRUCTIONS FROM THEIR COMPREHENSION AS A WHOLE" - MACH**

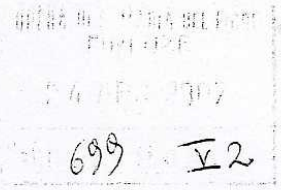
La Soprintendenza per i Beni Architettonici e per il Paesaggio per la Calabria agrees with MACH objectives and waits for the possibility to use the outcomes of the project.

IL SOPRINTENDENTE
Francesco Paolo CECATI

OPERA DI S. MARIA DEL FIORE
DI FIRENZE

FONDAZIONE 1296

Il Presidente



Dott. Piero Tiano
Coordinator
Istituto per la Conservazione
e Valorizzazione dei Beni Culturali
Consiglio Nazionale delle Ricerche
Via Madonna del Piano
50019 Sesto Fiorentino (Fi)

Oggetto: MACH – "Maintenance of the cultural heritage constructions from their comprehension as a whole".

This is to confirm that Opera di S. Maria del Fiore agrees with MACH objectives and waits for the possibility to use the outcomes of the project.

Best regards.

Florence, 23th april 2007

Dott.ssa Anna Mitrano

Associazione Dimore Storiche Italiane

Ente giuridicamente riconosciuto
Membro dell'Union of European Historic Houses Associations

Sezione Toscana

Egregio Professor
PIERO TIANO
Istituto per la Conservazione e Valorizzazione BB.CC.
Consiglio Nazionale delle Ricerche
Via Madonna del Piano - 50019 Sesto Fiorentino FI

21 aprile 2007

Egregio Professore

abbiamo esaminato lo schema generale del progetto MACH (Maintenance of the cultural heritage constructions from their comprehension as a whole) e ne condividiamo pienamente le finalità.

Nell'auspicio che il progetto possa avere uno sviluppo favorevole, anche in relazione alla conservazione delle dimore storiche private e loro pertinenze, ho il piacere di comunicarle l'adesione della Sezione Toscana del nostro sodalizio.

Molti saluti

Niccolò Rosselli Del Turco
Presidente della Sezione Toscana di A.D.S.I.

Borgo Santi Apostoli, 17 - 50123 Firenze - Tel. e Fax 055212452
e-mail: adsi.toscana@virgilio.it

Piattaforma Tecnologica Italiana delle Costruzioni - Area Patrimonio Culturale
Italian Construction Technology Platform – FA Cultural Heritage

Ancona, 26/04/2007

Dear Dr. Tiano,

I received your "MAINTENANCE OF THE CULTURAL HERITAGE CONSTRUCTIONS FROM THEIR COMPREHENSION AS A WHOLE – MACH" proposal for the FP7 and think it is of valuable interest for the sector of conservation of European Cultural Heritage. As representative of the Coordination Group of the ICTP and co-leader of the FA "Cultural Heritage", in accordance with the other co-leader prof. Claudio Modena, we will follow the project developments and are ready to present it inside the Platform, especially to SMEs that could be interested in exploitation activities.
Looking forward to future cooperation I thank you again for your invitation.

Best regards,

Eng. Enrico Esposito

Prof. Claudio Modena
Università degli Studi di Padova
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Prof. Dr.Ir.Arch. Koenraad Van Balen
Katholieke Universiteit Leuven
R. Lemaire International center for Conservation
Kasteelpark Arenberg 40
B-3001 Leuven (Heverlee)

LV/AS/TVDD/025-07/MWV

Antwerp, 23rd April 2007

Subject: Letter of support

Dear Sir,

With this letter I would like to confirm the participation of Monumentenwacht Vlaanderen in the **MACH-project** (Maintenance of the Cultural Heritage Constructions from their Comprehension as a whole). Our organisation agrees to be engaged as a subcontractor of the K.U.Leuven, partner in the project.

The primary task of Monumentenwacht Vlaanderen vzw will be to contribute in explaining the approach of Monumentenwacht and its methodology, to give a demonstration of an inspection and reporting on a real case in close collaboration with the partners in the project (on a building in Sicily, Italy) and to give advices and feed-back on a platform for monitoring and maintenance that the MACH-project will develop.

Monumentenwacht Vlaanderen expects, as an exemplary organisation that aims at promoting preventive conservation, monitoring and maintenance, that the outcome of this project will support and improve its methodologies and will promote this effective conservation approach in Europe. Monumentenwacht Vlaanderen will contribute to realising this result.

Looking forward to working with you on this project.

Yours sincerely,

Luc VERPOEST
President

PROVINCIE ANTWERPEN
provincie Limburg
provincie Oost-Vlaanderen
PROVINCIE VLAAMS • BRABANT
West-Vlaanderen
Met steun van de Vlaamse overheid

Generalitat de Catalunya
Departament de Cultura
i Mitjans de Comunicació
Direcció General del Patrimoni Cultural

Barcelona, April 13, 2007

European 7th Research Framework Programme (FP7)

On behalf of the Direcció General del Patrimoni Cultural de la Generalitat de Catalunya (Cultural Heritage Directorate of Catalan Autonomous Government), I am pleased to express the interest of our institution in the research and possible results of the collaborative project "MAINTENANCE OF THE CULTURAL HERITAGE CONSTRUCTIONS FROM THEIR COMPREHENSION AS A WHOLE" (MACH) to be submitted to next Cooperation call of the European 7th Research Framework Programme (FP7).

The *Direcció General del Patrimoni Cultural* is the Catalan institution responsible of the conservation, protection and documentation of the cultural heritage of Catalonia, including architectural heritage and historical construction. The *Direcció* cares for the conservation of thousands of monuments located in Catalonia, including cathedrals, churches, monasteries, castles and 20th c. heritage buildings.

We will be pleased to support the project by making available our experience in the study, conservation and maintenance of monuments and historical buildings of the Catalan territory. We understand that the outcome of the project, and particularly the creation of an expert system made accessible to institutions involved in architectural conservation, will contribute significantly to the better maintenance and conservation of monuments and ancient buildings.

Josep Ma. Carreté Nadal
General Director

Portaferrissa, 1 (Palau Moja)
08002 Barcelona
Telèfon 933 16 27 40
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MINISTERIO
DE CULTURA

DIRECCIÓN GENER
DE BELLAS ARTES
Y BIENES CULTURA

D. Santiago Sánchez Beitia
E.T.S. de Arquitectura de San Sebastián
Universidad del País Vasco
Barrio Barriera, s/n
48940 LEIOA
(Vizcaya)

Fecha: 27 de abril de 2007

Muy Sr. Nuestro:

Al tener conocimiento del proyecto que está desarrollando dentro del campo de la restauración sobre la utilización de técnicas no destructivas en la analítica de la patología de los edificios, quiero comunicarle el interés de esta Dirección General y apoyo al mismo. Quisiera solicitarte encarecidamente que tanto a esta Subdirección General como sobre todo al Instituto del Patrimonio Histórico Español facilitarse toda la información respecto del desarrollo del proyecto así como de su resultado final.

Aprovecho la ocasión para enviarle un cordial saludo. Queda a su disposición,

MINISTERIO DE CULTURA - Subdirec. Gral. Protección Patrimonio Histórico - DIRECC. GRAL. BB.AA. Y BIENES CULTURALES

Luis Lafuente Batanero
Subdirector General De Protección Del Patrimonio Histórico

MINISTERIO DE CULTURA
SUBDIRECCIÓN GENERAL DE PROTECCIÓN DEL PATRIMONIO HISTÓRICO
SECRETARÍA
27 ABR. 2007
REGISTRO DE SALIDA Nº 10.902

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48940 LEIOA
(Vizcaya)

Su ref
Nuestra ref N-102/GS/MO
Asunto
Fecha 2007-04-26

Muy Sr. nuestro:

Al tener conocimiento del proyecto que está desarrollando dentro del campo de la restauración sobre la utilización de técnicas no destructivas en la analítica de la patología de los edificios, quiero comunicarle nuestro interés y apoyo al mismo en el sentido de que si en el transcurso del proyecto se detectaran condiciones favorables para concretar el mismo en un trabajo de normalizacion, nosotros como organismo nacional y representante ante las entidades europeas e internacionales de normalización, podríamos promover dentro de nuestros órganos de trabajo el que dicha iniciativa de normalización fuera acogida favorablemente.

Aprovecho la ocasión para enviarle un cordial saludo. Queda a su disposición.

Gonzalo SOTORRÍO GONZÁLEZ
Director de Normalización