

Bowing: everything you should know

draft

Stefano Bianchini

HYGROTHERMAL STRESSES

Thermal stress in marble is a particularly critical issue. The basic observation is that calcite, and to a lesser extent dolomite, respond unusually to thermally induced stresses. Along crystallographic axis *c*, calcite has a thermal expansion coefficient of $26 \times 10^{-6} \text{ m K}^{-1}$ ($25 \times 10^{-6} \text{ m K}^{-1}$ for dolomite); in planes perpendicular to axis *c*, its coefficient is $-6 \times 10^{-6} \text{ m K}^{-1}$ ($6 \times 10^{-6} \text{ m K}^{-1}$ for dolomite). See Figure 1, after Kleber (1959) and Markgraf & Reeder (1985). When heated, a calcite crystal therefore expands in one direction while contracting in the perpendicular directions (Figure 2).

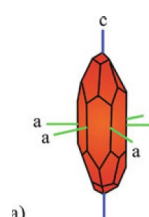


Figure 1. Thermal expansion of calcite and dolomite.

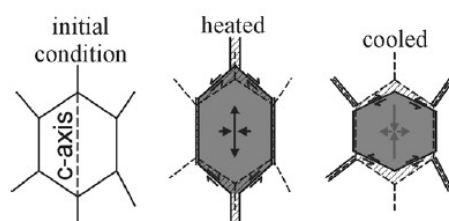


Figure 2. Change in shape as a function of temperature.

In marble, a polycrystalline material, temperature fluctuations generate tensile, compressive and shear stresses at grain boundaries, depending on the orientation of the individual crystals.

[Working note in the original: “Check whether the Siberian...”]

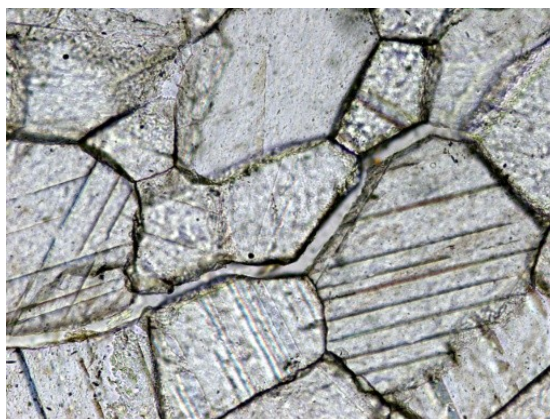
In some marble varieties these stresses cause new grain-boundary microcracks to form, a phenomenon known as granular decohesion (see photographs).

Under thermal stress, the density of microcracks per unit volume increases. Once a critical microcrack density is exceeded, the stone's failure mechanism changes: normally transgranular failure, involving cleavage within the crystals, becomes intergranular fracture, along grain boundaries. Mechanical properties then deteriorate markedly.

Changes in the crystalline structure of solids, even at relatively low temperatures, are already recognised in several areas of solid mechanics. For example, steels modify their crystal lattice at temperatures as low as 150°C . It should therefore come as no surprise that some marbles exhibit “anomalous” behaviour at $60\text{--}70^{\circ}\text{C}$.



Advanced granular decohesion in white Gioia marble. As shown, the alignment of small-scale fractures (microfractures) produces an intergranular defect visible to the naked eye.



Enlarged detail. In some crystals, bonding at the grain boundaries has been completely lost as a grain-boundary fracture propagates.

In the marble industry, this phenomenon became prominent with the widespread use of stone panels only a few centimetres thick, exposed to temperature changes. In this situation, granular decohesion becomes the principal failure mechanism. It must be stressed that not all marbles behave in the same way. Some are not thermally sensitive, or at least not at temperatures around 60–70°C. Of the approximately 200 marble varieties in the Apuan-Versilia basin, only some show the forms of deterioration described later. Others are neither thermally sensitive nor subject to durability problems when exposed to thermal stresses in a humid environment.

From a scientific standpoint, there is still no satisfactory micromechanical failure model defining thermally induced failure. Research in rock mechanics on dimension stone in general, and marble in particular, is also very limited, both at rock-mass scale and in terms of small-scale behaviour.

This does not mean that rock mechanics itself is inadequate. Rather, there has historically been little interest in understanding these particular failure phenomena. Interest has emerged only in recent years, and mainly at a few research centres in northern Europe, which are currently the leading specialists in small-scale marble mechanics.

Rock mechanics is an extremely broad and varied subject, both in the problems it addresses and in the types of rock involved. Its models are generic and can consequently prove inadequate, at both small scale (decohesion and bowing) and large scale (rock-mass stability and underground tunnels).

Fortunately, at small scale, the striking damage to the marble at Finlandia Hall led to a new research focus involving SINTEF and the University of Göttingen, Germany. Small-scale marble mechanics has therefore emerged as a field only relatively recently.

Technically, we are about a century behind research on metals. Contrary to popular belief, metals also presented devastating problems, which were resolved through the development of micromechanical failure models that are now very reliable. This progress nevertheless required numerous ship sinkings, train failures and crashes involving Comet aircraft.

The large-scale behaviour model for a marble must be derived from its micromechanical failure model. It is therefore essential, as it was for metals, to begin by studying crystals, their interactions, and the changes induced by temperature and moisture, including ice and water vapour, in order to propose a valid failure model.

The problem is further complicated by marble's anisotropy, both mechanical (elastic modulus, stiffness and so on) and physical (permeability). For example, marble already affected by decohesion has been observed to have greater permeability along its preferred fabric direction, known as the “verso”, than through the rest of the rock matrix. The photographs show marble treated with a red dye penetrant.

After a few hours, the penetrant reached the opposite face, travelling preferentially through the minerals defining the verso. In this marble, the verso introduces a factor that can hardly be ignored in a micromechanical durability model, in which moisture and the way it is transmitted play a fundamental role.

Preparation: stage 1.

Preparation: stage 2. The penetrant is shown in red.





Lower face: the penetrant reached this face by following the verso direction.



Lower face: the penetrant appeared along the pattern of the verso.

Lower face: penetrant transmitted along the verso.

This article retraces the key stages in the development of small-scale marble mechanics. Here, “small scale” refers to the phenomena associated with durability problems in external cladding. It begins with Franzini's 1983 papers on marble “cooked” by temperature and proceeds to more recent findings on the influence of moisture in interpreting phenomena such as bowing and volumetric expansion.

In 1983, in “Degradazione del marmo per effetto della temperatura” [Marble deterioration due to temperature], Franzini proposed an outline qualitative microstructural model taking account of thermally induced granular decohesion. The authors called the decohered material “cooked marble”, borrowing a term still used by quarry workers. The parameters analysed were the water absorption coefficient, flexural elastic modulus and textural characteristics.

For flexural elastic modulus, heating to 100°C for three hours was shown to cause a reduction ranging from 18% to 76%, depending on the marble type. For water absorption, the test's drying procedure alone, at 105°C, produced an increase in the absorption coefficient ranging from 43% to 133%.

Franzini and colleagues correlated increased absorption with an increase in “semi-closed” and/or intergranular porosity: the portion of porosity whose mechanism is linked exclusively to the existence and development of microfractures between grains. Regarding texture, tests at various temperatures, including 500°C, did not significantly increase twinning, but did increase grain-boundary microcracking.

The independence of twinning from temperature therefore excludes an entire part of solid mechanics, as applied to metals, associated with the formation of new twins and perhaps also atomic dislocations. [Continued on the next page.]



On the evidence available, we must therefore provisionally consider that thermally induced damage does not cause electron movements and hence the propagation and displacement of line defects. From field observations, the authors concluded that the “cooking” phenomenon begins at temperatures of only a few tens of degrees Celsius, although this finding was not supported by experimental evidence.

After 1983, about twenty years passed before marble durability returned to the scientific agenda.

Meanwhile, the marble installed at Finlandia Hall in 1971, specified by architect Alvar Aalto, was developing bowing. By 1985 some panels had curved by as much as 5 cm. A few years later, another emblematic case emerged: the Amoco Building.

The skyscraper, completed in 1974, was entirely clad in marble. The selected marble immediately proved thermally sensitive and prone to bowing. In 1988, 30% of its 44,000 panels showed curvature greater than 1.5 cm. All the marble was replaced with another stone, at a cost of approximately one third of the cost of the entire skyscraper.

In response to the Finlandia Hall problems, and with the involvement of the City of Helsinki's Public Works Department, the EU funded the first project intended to lay the foundations of marble mechanics. The project was called “Developing long-term durability of marble façades”, abbreviated to MARA.

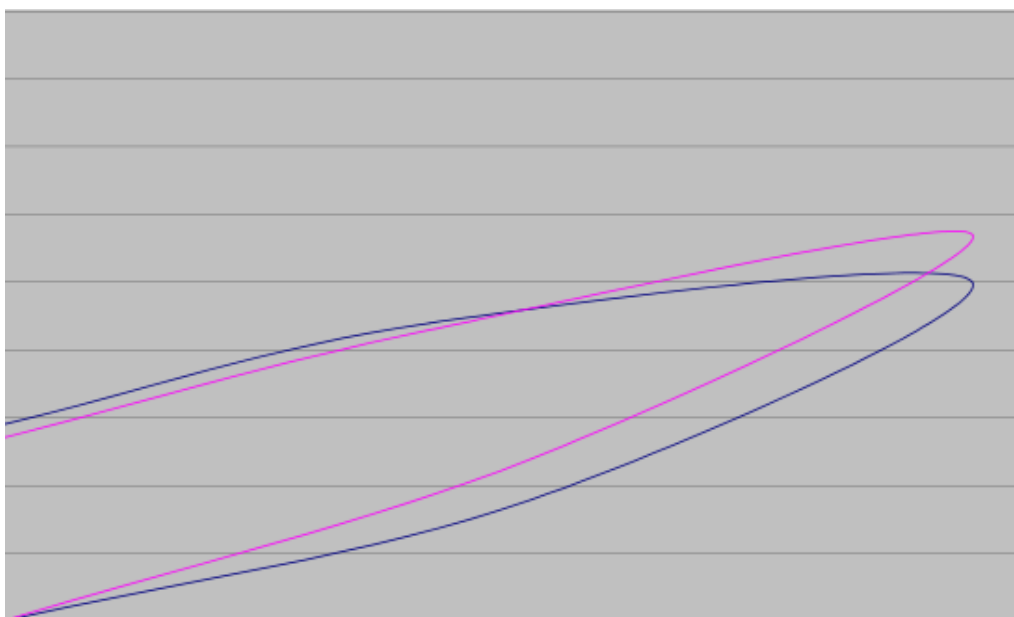


The extent of thermally induced damage depends essentially not only on the anisotropy of the single crystal, but also on the orientation of individual calcite crystals and the shape and size of their grains (Siegesmund et al., 2000).

Zeisig et al. (2002) analysed reduced thermal resistance and the associated physical weathering, drawing on systematic investigations of 18 marbles. Expansion coefficient α , which describes the change in length during heating and cooling, depends on the temperature interval considered.

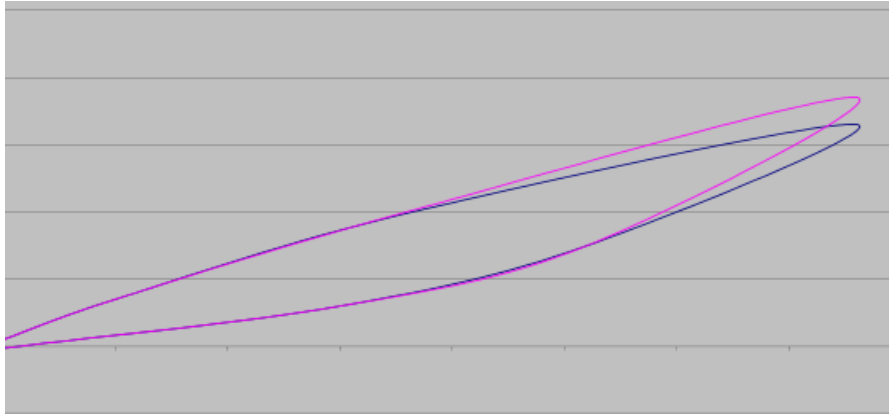
In general, thermal expansion increases as temperature rises and, after cooling, the material in most cases does not return to its initial state. The remaining residual expansion produces changes in length and volume that can be explained by progressive microfracture formation. Zeisig et al. (2002) distinguished four types of expansion behaviour, summarised in the following diagrams.

Type I: isotropic expansion coefficient and large isotropic residual expansion after cooling.



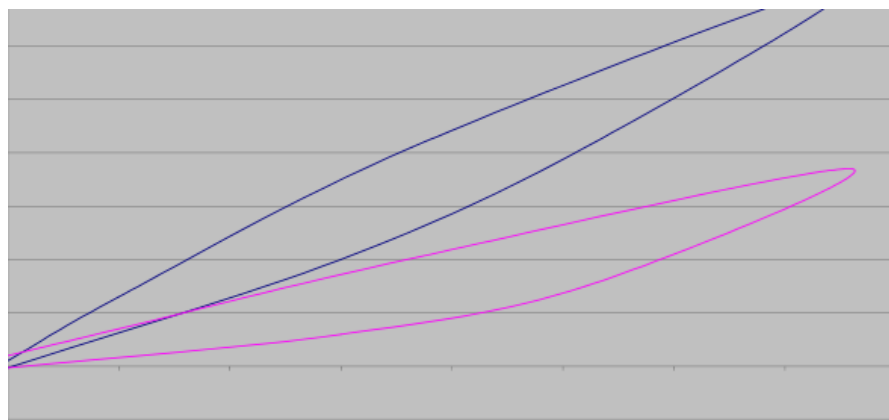
Horizontal axis: Temperature. Vertical axis: Strain [mm/m].

Type II: isotropic expansion coefficient and zero or minimal isotropic residual expansion.



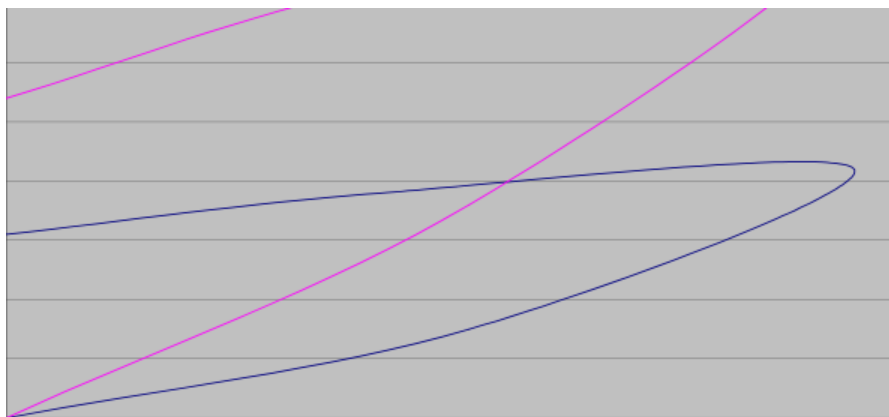
Horizontal axis: Temperature. Vertical axis: Strain [mm/m].

Type III: anisotropic expansion coefficient and zero or minimal isotropic residual expansion.



Horizontal axis: Temperature. Vertical axis: Strain [mm/m].

Type IV: anisotropic expansion coefficient and anisotropic residual expansion.



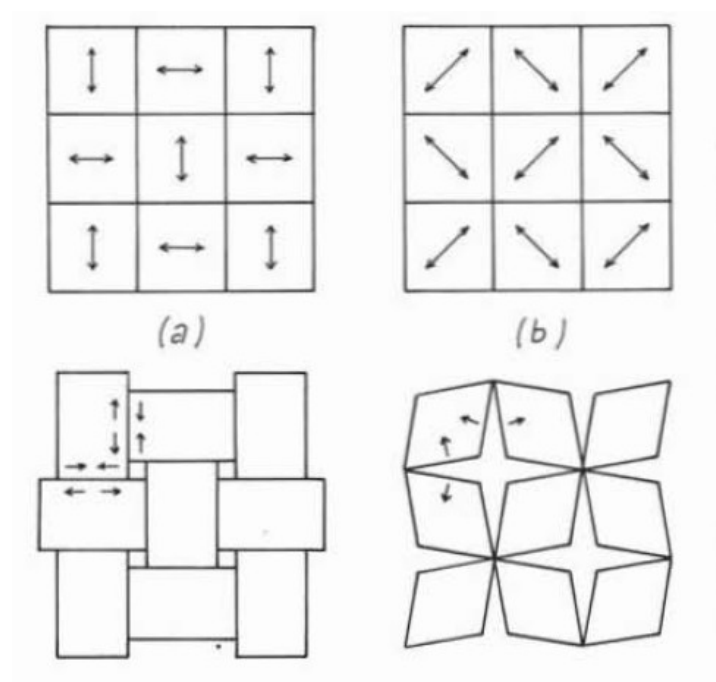
Horizontal axis: Temperature. Vertical axis: Strain [mm/m].

Thermally induced effects begin at grain boundaries, where thermal expansion propagates microfractures and further weakens the bonds between crystals. The phenomenon has been studied by numerous authors. [The following sentence is incomplete in the original.]

Two forms of porosity are mentioned: “open” or intergranular porosity, and “semi-closed” intra- and/or intergranular porosity. The increased water absorption coefficient after heating to 100°C is caused by increased semi-closed porosity following separation between calcite grains.

In some marbles, granular decohesion begins at relatively low temperatures: temperatures as low as 40-50°C have been shown to be sufficient.

Chemical composition, grain size and shape, grain-boundary geometry, fabric, and the influence of pre-existing microcracks have been identified as critical parameters in thermally induced strength reduction. [Continued on the next page.]



Physical aspects related to construction, together with other extrinsic influences such as climatic conditions, are initially kept unchanged.

Figure 1. Basic models of thermal expansion in marble. Marbles may exhibit isotropic (a, c) or anisotropic (b, d) expansion. Thermally sensitive marbles may also show permanent residual expansion after a single heating event, whereas marbles that are not thermally sensitive return to their original length (a, b). The arrows show the direction of the curves during specimen heating and cooling.

The following discussion considers specimens with differently oriented structural elements. This makes it possible to determine the influence of directional dependence or, equivalently, the maximum and minimum expansion of a marble. Like other physical characteristics, thermal expansion is direction-dependent, that is, anisotropic, and can therefore vary considerably.

To account for the conditions to which marble is exposed when used as building façade panels, moisture must be considered. Studies show that physical weathering, ultimately causing façade panels to bow, is closely linked to the material's irreversible expansion. The question is therefore which climatic influences produce such high residual expansion. The literature reports substantially higher expansion coefficients (GRIMM, 1999). Moisture consequently plays a key role (BUCHER, 1956; WINKLER, 1996; KOCH & SIEGESMUND, 2004B; GRELK ET AL., 2004).

Moisture alone, however, does not cause residual expansion. Hygric expansion was measured in specimens of Peccia and Carrara marble after 48 hours of water saturation. No expansion was detected, consistent with the technical literature. POSCHLOD (1990), for example, observed hygric expansion after 24 hours of water absorption in Carrara and Laas marble of 0.006 and 0.012 mm/m respectively.

Conversely, temperature cycling under dry conditions produces only limited residual expansion, which does not continue to increase even with further repetitions (SAGE, 1988).

To understand the role of water during temperature cycling, Peccia, Carrara 1a and Ruivina specimens were heated to 90°C, first eight times under dry conditions and then ten times under wet conditions (Figure 2). Only the first dry heating cycle caused a substantial increase in residual expansion. Its progression ceased between the second (PE) and fifth (GI) cycles.

Under the influence of moisture, progressive residual expansion changed fundamentally: it increased continuously. After ten wet cycles, the increase was relatively small in Peccia marble (0.25–0.59 mm/m) and slightly greater in Ruivina marble (0.27–0.76 mm/m). Carrara 1a showed the greatest residual expansion, ranging from 0.80 to 1.28 mm/m.

As with residual expansion under dry conditions, progressive residual expansion under hygrothermal action displayed marked anisotropy. After ten wet cycles, Ruivina marble showed residual expansion in direction Z three times greater than in direction X, in which specimen length remained approximately stable after only a few wet cycles. Directional dependence in Carrara 1a was comparatively less pronounced.