Selecting a safety factor for stone

At least five different methods have been proposed, but none is widely accepted yet

By Christine Beall

To avoid failure, building materials are allowed to carry only a fraction of their ultimate strength. The ultimate strength of a material is the load it carries at the moment it fails. The amount of stress a material is allowed to carry is called its allowable design stress, which usually is calculated by dividing its ultimate strength by a safety factor. Each material has its own safety factor, set either by building code or by the judgment of the engineer.

Safety factors provide a margin of safety to account for unquantifiable factors: temporary loads, such as high wind gusts, ice, and projectile impact; imperfect workmanship; manufacturing variations; and transportation, handling, and erection stresses. A safety factor of 2 means the allowable stress is only ½ the ultimate strength of the material.

Some experts have called safety factors "factors of ignorance" (Ref. 1). That is because safety factors are larger when loads and stresses are uncertain, when the material strength is highly variable, and when the material is not very forgiving. Safety factors are larger (and allowable design stresses are lower) when the behavior of the material and the loads are less known.

Safety factors for stone have always been conservative compared with safety factors for ductile materials like steel. For example, most structural steel has a safety factor of 1.8. Safety factors recommended by stone industry associations, on the other hand, range from 3 to 8 (Table 1).

TABLE 1
SAFETY FACTORS RECOMMENDED BY STONE ASSOCIATIONS

Granite	3 (Ref. 5)
Anchorage components in granite	4 (Ref. 5)
Marble veneers	5 (Ref. 6)
Limestone veneers	8 (Ref. 7)

One reason stone safety factors are more conservative is that stone is a natural material and not a closely controlled, manufactured product. The physical properties of stone, even the same type of stone from the same quarry, can vary widely. Some stones also lose strength after repeated heating-cooling and freeze-thaw cycles. And some gain or lose strength when they're saturated.

New proposals

Encouraged by intense competition in the curtain wall market, several experts have proposed new, more liberal safety factors for stone. The smaller the safety factor, the more efficient and economical the material. No longer is building stone used the way it was 200 years or even 50 years ago. To make stone cost competitive for commercial buildings, it is now cut very thin (sometimes as thin as ⅝ inch). The thinner panels cost less and weigh less, thus reducing shipping, erection, and structural frame costs.

The traditional stone safety factors that have been recommended by stone industry associations (Table 1) are empirical recommendations. They're not derived from tests or from engineering analysis, but have evolved as industry rules of thumb. The desire to make natural stone more economical has encouraged—and required—the development of several newer, rationally determined design methods. Intended to replace the empirical recommendations, most of the new proposals for stone safety factors are controversial. None is yet widely accepted.

As early as 1981, Alex Gere of Stone Tech, Inc., Long Island City, New York, proposed that stone safety factors be based on the variation in flexural strength test results as well as on the type of stone (Ref. 2). According to Gere, a narrow range of test results indicates a stone with more consistent physical properties. A wider range shows a stone with more varying properties. Thus the greater the variation in test results, the greater the safety factor should be.

Based on this theory, Gere developed the recommendations for safety factors shown in Table 2. These safety factors are generally more conservative than traditional industry guidelines. Some people say they unnecessarily complicate the issue and raise the cost of stone veneers.

In 1987, John McCabe, Jr., of Structural Engineering, Inc., Arlington, Texas, also proposed safe-

ty factors based on variations in test results (Table 3). McCabe used a modified ASTM C 880 flexural test procedure, using larger, thinner, longer specimens loaded in a manner "more consistent with actual wind loading" on a stone curtain wall. McCabe's safety factors for granite are more liberal than those recommended either by Gere or by the National Building Granite Quarries Association. He does agree with Gere, though, that safety factors should be higher if the test results are erratic and lower if test results are consistent.

In 1988, Bernhard Wonneberger and Seymour Bortz of Wiss, Janney, Elstner Associates, Northbrook, Illinois, argued that the effects of weathering on stone should be considered when calculating safety factors. By comparing the effects of accelerated laboratory weathering on marble with marble that had been weathered naturally for 8 years, Wonneberger and Bortz found that accelerated weathering tests could be used to predict durability. After performing accelerated weathering tests on samples of marble, granite, and limestone, they recommended that McCabe's safety factors be doubled, as shown in Table 4. To calculate safety factors directly, Bortz and Wonneberger multiply a wind factor by a stone variability factor by a weathering factor.

Two articles published in 1989 by Charles Clift and Jeffrey Bayer of Curtain Wall Design Consulting, Inc., Dallas, Texas, presented a new theory of stone cladding design based on probability of risk. Rather than look at safety factors to determine allowable stresses, Clift and Bayer asked what risk of failure is acceptable. By comparing the one per million probability of failure used in nuclear design and the 8 per 1,000 for glass, they proposed a 1 in 10,000 probability of risk for natural stone cladding. This is equivalent to a 50% confidence level that 99.20% of the panels will not fail.

This method is called the probability of stone failure theory (PSFT). The allowable stress for a particular stone is calculated in four steps, as outlined in the box. Table 5 shows a comparison of allowable stone stresses calculated by the PSFT method and the various safety factor recommendations discussed above.

Clift and Bayer admitted that the 1 per 10,000 risk factor would cause debate. And they were correct. Says Bortz and Wonneberger: "While we do agree with them regarding this concept [probability based design approach], we think a great deal more work and discussion needs to be performed be-

TABLE 2 SAFETY FACTORS RECOMMENDED BY ALEX GERE

Spread in Test Results[1]	Safety Factor for Calculating Stone Thickness	
	For Wind Load	For Lateral Loading[2]
Igneous rock (Granite)		
Up to 10%	3.0	4.5
10% to 20%	4.0	6.0
More than 20%	6.0	8.0
Metamorphic rock (Marble)		
Up to 10%	4.0	6.0
10% to 20%	5.0	7.5
More than 20%	7.0	10.0
Sedimentary rock (Limestone)		
Up to 10%	5.0	7.5
10% to 20%	6.0	9.0
More than 20%	8.0	12.0

[1] Gere recommends a minimum of five test specimens, all from different stone slabs.

[2] Gere also recommends laboratory testing of the full-scale anchoring system when possible. Based on a minimum of five pull-out test results for anchoring stone, he permits use of the same safety factors given in the table for wind load. Without testing, he recommends the more conservative lateral anchoring safety factors.

Source: Ref. 2.

TABLE 3 SAFETY FACTORS FOR GRANITE RECOMMENDED BY JOHN McCABE, JR.

Coefficient of variation	Safety factor
0-3%	2.5
3%-9%	3.0
9%-20%	3.5
20% and greater	4.0

Based on test results from at least six tests.

Source: Ref. 8.

TABLE 4 SAFETY FACTORS FOR GRANITE RECOMMENDED BY BORTZ AND WONNEBERGER

0-3%	5.0
3%-9%	6.0
9%-20%	7.0
20% and greater	8.0

To allow for weathering of stone, safety factors recommended by John McCabe, Jr., in Table 3 are doubled.

Source: Ref. 1.

Calculating Allowable Stress Using the Probability of Stone Failure Theory

Using the 1 in 10,000 probability of risk recommended by Bayer and Clift (Ref. 10), the allowable stress for a particular stone can be calculated in four steps:

1. Perform tests, preferably a modified ASTM C 880 flexural test, using 8x36-inch specimens with the thickness and finish to be used on the job. For each test condition (wet, dry, parallel to grain, perpendicular to grain), test at least five samples.

2. Calculate the average and standard deviation for each of the four test conditions.

3. Calculate the bending stress at a probability of failure of 1 per 10,000 as follows:

Bending stress = Average - (Standard deviation x coefficient from table)

4. Calculate the allowable bending stress by dividing the bending stress calculated in Step 3 by 1.3, the wind load factor for curtain walls.

The lowest allowable stress for the four conditions is the one that is used in design

STANDARD DEVIATIONS TO BE SUBTRACTED FROM 50% CONFIDENCE FACTOR AND 1 IN 10,000 PROBABILITY OF FAILURE

Number of Samples	Standard Deviations to be Subtracted
2	5.468
3	4.447
4	4.175
5	4.050
6	3.979
7	3.933
8	3.900
9	3.877
10	3.858
11	3.844
12	3.832
13	3.822
14	3.814
15	3.807
16	3.801
17	3.796
18	3.791
19	3.787
20	3.784

TABLE 5 ALLOWABLE DESIGN STRESSES CALCULATED BY DIFFERENT METHODS (PSI)

Method of Analysis	Stone #1	Stone #2
Probability of stone failure theory (Ref. 9)	1401	251
Industry standard	630	452
National Building Granite Quarries Association (Ref. 5)	525	377
Alex Gere (Ref. 2)	525	188
John McCabe, Jr. (Ref. 8)	525	283
Wonneberger and Bortz (Ref. 1)	263	141

Source: Ref. 9.

fore it can be adopted for stone design purposes."

Bortz and Wonneberger disagree with the PSFT method on three points: 1) five specimens taken from one area of stone is not large enough to represent the true variability of stone (they recommend at least 30 panels, six each from five different stone blocks); 2) a 50% confidence level is not adequate (they recommend at least 90%); and because most high-rise stone clad buildings have more than 10,000 panels, a 1 in 10,000 risk of failure is too great (they recommend 1 in 100,000 instead).

Probability based design, say Bortz and Wonneberger, "should only be used by a prudent designer with a great deal of caution, and only with test data from a large test population. At the present time, designers should stay with the industry standard values, unless they are sure of the accuracy of the standard deviation they are working with."

The Uniform Building Code (Ref. 3} requires that all anchored veneers, including stone, be "designed to resist a horizontal force equal to twice the weight of the veneer." This is the maximum allowable stress. The code also prescribes that the veneer be at least 2 inches thick and no more than 20 square feet in area. Anchors (dowels or wire ties) may be spaced no more than 24 inches apart around the perimeter of the panel.

James Amrhein and others of the Masonry Institute of America, Los Angeles, recently tested four common stone anchoring systems to determine what safety factors these code requirements would give. Three of the anchor systems (wire ties, dowels, and bent bolts) were well above the industry standard safety factors for most of the stones tested (Ref. 4). However, enough of the anchor systems (especially straps and kerf) were below recommended safety factors to prove the value of preconstruction testing of any proposed panel or anchor system design.

Safety factors aren't cure-alls

How should engineers determine the allowable design stress for a natural building stone? What safety factor should they use? In today's competitive curtain wall market, where stone is cut thinner and thinner, the answer is no longer simple. You must follow the governing building code of course. You also can use the traditional safety factors recommended by the stone associations. Or you can follow one of the proposals described here, realizing none has been widely endorsed yet. As Bortz and Wonneberger say, "there is considerable variance of opinion regarding what is a reasonable safety fac-

tor for stone."

But even large safety factors and minimum prescriptive code requirements are not substitutes for the rational design of stone veneer. Today's thin stone veneers must be designed to accommodate calculated thermal expansion and contraction, expected differential movement, creep, deflection, vibration, high wind pressures at building corners and roofs, and other known variables. Code requirements for maximum anchor spacing may not provide the right safety factor for the specific type of anchor and stone you're using. Safety factors should be used only to accommodate unknown stresses.

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