BUILDING ENVELOPE TECHNOLOGY SYMPOSIUM

Thin Marble Façades: History, Evaluation, and Maintenance

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ABSTRACT

Thin marble panels have been used on buildings since the mid-twentieth century, yet marble panels have continued to fail at an increasing rate. Once a structure is known to be experiencing hysteresis, a licensed consultant must make decisions on the evaluation process, frequency of observations, temporary stabilization, and/or panel replacement. An overview of nondestructive testing techniques and up-close visual observations used to produce graphical output for presentation in a comprehensive manner will be discussed. This presentation will also review the history of marble façades, various design techniques, numerous deterioration mechanisms, common methods of assessment, and successful maintenance recommendations.

SPEAKER

Daron Hester, PE — Walter P. Moore and Associates, Inc.

Daron Hester is a project manager in the Structural Diagnostics Services Group at Walter P. Moore. Hester has overseen the assessment and evaluation of numerous building façade cladding systems, including thin marble veneers, brick veneers, precast concrete panels, and exposed concrete structures. In addition to assessment and evaluation, Hester has developed repair documents for these distressed building façades, ranging from emergency overhead protection and temporary stabilization of distressed marble panels to complete recladding of the severely cracked marble cladding components of a 43-story high-rise office building.

Thin Marble Façades: History, Evaluation, and Maintenance

INTRODUCTION

Thin marble panels (thickness of 5 cm or less), have been a popular cladding material on buildings since the mid-twentieth century. Even so, marble panels have continued to fail at an increasing rate, despite enhanced knowledge in the technology of marble façades. Design and installation techniques for thin marble façades have evolved considerably. Though a number of deterioration mechanisms exist for marble façades, hysteresis (irreversible material expansion) tends to be the most damaging. If a marble façade is found to be experiencing hysteresis, an evaluation and repair program should be provided by a licensed professional engineer specializing in the assessment and restoration of façades. The evaluation of a façade experiencing hysteresis may consist of up-close visual observations of 100% of the façade, nondestructive evaluations (NDE), exploratory openings, and destructive testing. Repair of a marble façade typically consists of temporary stabilization, frequent monitoring, and up-close observation. A thin marble façade requires an ongoing maintenance program for the life of the building, regardless of age or currently observed deterioration.

HISTORY

Because of its aesthetic qualities and the relative ease with which it can be worked, marble has been in architectural use for as long as man has been building. Over the last several millennia, the use of marble on building exteriors has evolved from massive bearing walls of solid stone to highly attenuated cladding panels hung from the superstructure. These paneled exteriors, or thin-stone veneers, gained in popularity in the mid-twentieth century. Architects and building designers were attracted to the comparatively lower cost and lower weight of a thin-stone system versus traditional stone construction. Additionally, the inability to acquire dimension blocks in certain marble types, particularly among American marbles, contributed to the popularity of thin-stone veneers.

By the early 1950s, thin-stone veneers had become accepted systems for building cladding, and dozens of design and engineering handbooks on their use went into publication even before 1960. In the 1970s, thin-stone veneers reached a peak in their usage. Despite the enthusiasm the building community exhibited for them, there was very little true understanding of the performance or serviceability of these systems, many of which began to deteriorate rapidly after completion.

Several infamous case studies of systemic failure of marble thin-stone veneers have been heavily published, with the most noteworthy being Alvar Aalto's Finlandia Hall in Helsinki, Finland[1] (*Figure 1*). Completed in 1971, the modernist concert hall was clad in thin panels of Carrara marble, an icy-white Italian stone that was poorly suited to the harsh climate of Finland. Within only a few years, noticeable deformation of the cladding panels had begun. By the late 1980s, safety and aesthetic issues necessitated a major renovation of the marble veneer. Because Finlandia Hall is a cultural icon and protected by law by the Finnish National Board of Antiquities, restoration of the exterior was a heavily regulated and highly political process. Although the material properties of the Carrara marble were determined to be a leading factor in the deterioration of the cladding system, the restoration was ultimately limited to the reuse of Carrara for the new façades.

In an effort to reduce the potential for future deformation and deterioration of the marble, the new façade was designed to provide flexible connections for the stone panels, which in theory would reduce the internal stresses in the stone created by the supporting hardware. Additionally, the replacement marble was required to have superior flexural strength, although the original thickness of the marble of less than 1½ in would be maintained in the replacement units. The restoration was completed in 1999, and, within just two years, deformation of new panels was observed. The continued deterioration of the original and replacement panels at Finlandia Hall exemplifies the typical distress conditions and the difficulties encountered when repairing thin-stone veneers.

Another important case study is that of the 80-story AON Center (formerly the Amoco Building) in Chicago[2] (*Figure 2*). Six marble types were originally evaluated for use on the façade, and after careful consideration, Carrara Alpha Gray marble was selected. The effects of weathering were known and flexural strength testing was performed before and after thermal cycling in an attempt to simulate anticipated conditions.

Completed in 1972, the building was clad with 44,000 panels that were typically 1¼-in thick, and by 1979, evaluation of the façade had found cracks in the panels. A majority of the cracked panels were located on the elevations that received the most sun exposure, and it was concluded that thermal cycling had caused the cracking. The most shocking conclusions were reached after laboratory testing was conducted on

panels removed from the building and on additional virgin panels. It was found that the flexural strength assumed from the original testing was much lower than that of panels actually installed on the building. Testing concluded that within 10 years of testing, the marble panels would lose a total of 70% of their original flexural strength. All panels were eventually removed from the building, and, by September 1991, 44,000 marble panels had been replaced with Mount Airy granite.

Above and beyond iconic failures of thin-stone veneers like Finlandia Hall and the Amoco Building, the authors of this article have extensive first-hand experience with the poor performance and persistent serviceability issues this cladding system regularly exhibits. Panels as thin as five-eighths inch have been observed in a 1951 thin-stone veneer using Georgia Pink marble, although seven-eighths inch seems to be a standard thickness for façades dating to the 1960s and 1970s. In each of the buildings encountered, "bowing" or "cupping" deformation of the marble, along with cracking of the panels, has caused serious concerns about the integrity of the façade system. In some cases, advanced deterioration of the panels has resulted in localized failure of the veneer.

DESIGN TECHNIQUES AND SYSTEMS

Since modern stone is treated as the skin of a building rather than the skeleton, anchorage systems have been required to attach the stone to the structural backup system. These attachment systems must be properly designed to resist forces and design conditions that have been negligible in the past. The stone properties, metal anchorage systems, and moisture infiltration are a few of the modern problems designers face to keep a marble façade safe and functioning as intended. A full discussion of thin-marble design techniques and systems is beyond the scope of this paper, so a brief overview will be given. The proper design of a thin-stone marble system must be done with the aid of building codes and design guides, taking into consideration the weather conditions of the place where the façade will be built, as well as the long-term durability characteristics of the stone materials.

It should be noted that we are limiting our discussion to marble veneer. Sizes for marble veneer are typically listed in metric; and, therefore, the English equivalents are only approximate. The typical thicknesses of marble veneer are 2 cm, 2.5 cm, 3 cm, 4 cm, and 5 cm. The size of the panel will vary depending on stone properties, and a stone supplier should be contacted for information on a particular marble.

Marble design has changed since its beginnings in the mid-twentieth century, and following today's guidelines can help the designer specify a well-performing system. When specifying a new marble façade, an historical precedent should be in place for the type of stone being used in a particular region. While accelerated weathering testing should be conducted, these cannot be relied on solely for material performance. The best way to predict whether or not hysteresis will occur in a particular system is to compare it to a similar system under similar conditions.

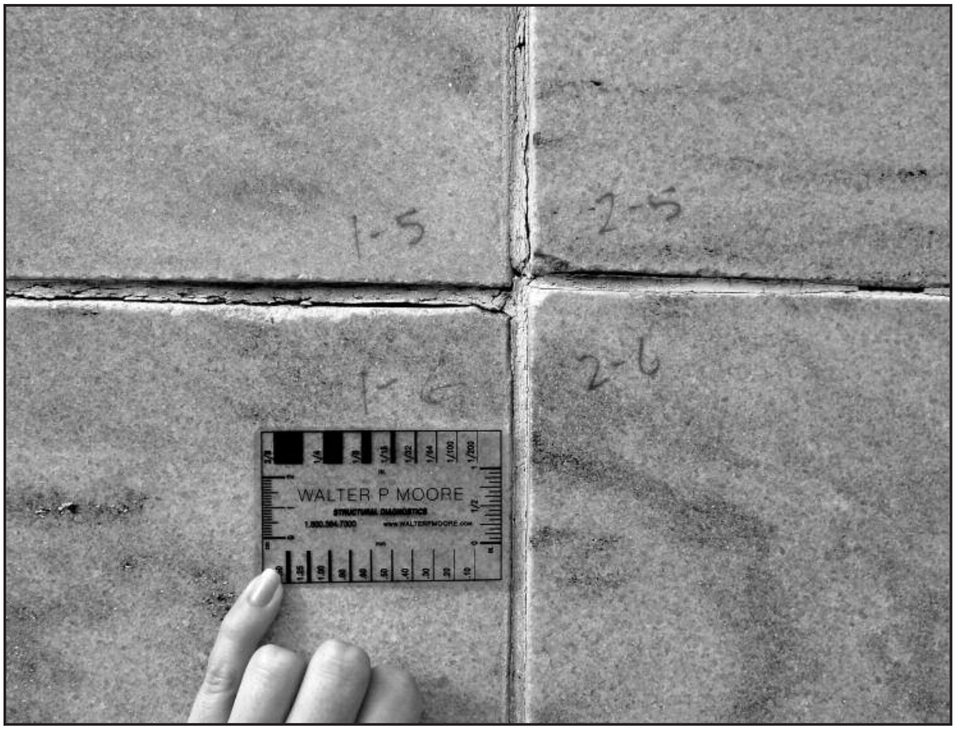
The Masonry Institute of America has given design requirements in the publication *Marble and Stone Slab Veneer.*[3] Important issues to consider in the design of a stone veneer include the following:

LOADS

- Gravity, load-bearing anchors
  - Wind loads
  - Earthquake loads
  - Additional loads on backup system from veneer
- The lateral force the system is designed for should be at least twice the weight of the marble panels.
- Façade framing should be noncombustible and corrosion-resistant.
- Façade framing should not be more than 25 ft off the ground and not spaced more than 12 ft thereafter.
- Differential movement of stone and backup system
  - Lintels and horizontal supports should limit deflections to one-five-hundredth.
  - Inadequate movement joints can cause the type of distress shown in *Figure 3*.
- Thermal movement
  - Average coefficient of thermal expansion for marble is 7.3 (in/°F) x 10^{-6}.
- Deformation
  - Shrinkage
  - Deviations
  - Freeze/thaw

While building codes vary depending on the local jurisdiction, the International Building Code is used in many locations and will be referenced throughout this paper as the governing design code. The 2006 International Building Code's (IBC) Chapter 14 presents provisions for exterior walls. Section 1405.6 lists the two methods in which stone veneer (less than 10 in thick in this case) shall be anchored directly to masonry, concrete, or stud construction:

- For a backup of concrete or masonry, corrosion-resistant anchor ties are required to be laid in the mortar



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joint every 12 in. A wire tie is required for every 2 sq ft of area. The legs of the loops are to be laid in the backup mortar joint and stone veneer mortar joint. One-inch-thick cement grout is required to be placed between the backing and the stone veneer.

- For a backup of wood studs, wire mesh is applied over the studs. Corrosion-resistant wire is then looped through the mesh for every 2 sq ft of area. The tie shall lie in the stone veneer mortar joint. One-inch-thick cement grout is then placed between the backing and the stone veneer.

A leading design guide for thin marble is the *Dimension Stone Design Manual (*hereinafter the *Manual)*, first published in 1971 by the Marble Institute of America (MIA).[4] The MIA is a leading source of information related to natural-stone design and application of stone products. The *Manual* gives design information that represents the current practice in the industry. The membership of the MIA consists of natural-stone producers, exporters/importers, distributors/wholesalers, fabricators, finishers, installers, and industry suppliers. The intent of this manual is to give information to facilitate natural-stone use in architectural design.

Techniques for marble panel installation have evolved over the years, and wholly new systems have been developed beyond the original methods used in the mid-twentieth century. Three methods of installation are typically used as follows:

1. The standard set system with vented or filled cavity
   A. Mortar spots at backup at 18 in apart
   B. Joints should be maintained between panels.
   C. Expansion joints in both directions should be at 20 ft maximum.
   D. Support angles at openings and each story with ¼-in weeps
   E. Vents and drainage provided at 5 ft horizontal and 20 ft vertical maximum
2. Mechanical systems
   A. Mechanically attached to a backup panel system of welded metal studs.
   B. Curtain wall members: in glazing channels.
   C. Installed in structurally glazed curtain walls
3. Other systems
   A. Stone attached to various backup materials by using epoxy, latex Portland cement, or silicone.

Stainless steel #8 wire anchors are now recommended. It is recommended that four anchors be provided for panels up to 12 sq ft with two additional anchors for each additional 8 sq ft of surface area. It should be noted that this is less conservative than the IBC requirements. Plastic shims are used between panels to maintain the joint between panels. Weep tubes are placed in joints where moisture may accumulate within the wall, such as at the base of a cavity, continuous angles, flashing, etc.

The design of anchors should be in accordance with ASTM C1242, Standard Guide for Selection, Design, and Installation of Dimension Stone Anchoring Systems. For additional information, also see the paper, *Anchoring Exterior Stone.*[5] Stone anchors are categorized as one of four types:

1. For general cladding applications, the following are available for use: rod, tooled rod, strap, wire, adhesive embedded, and disk anchors.
   A. Rod anchors are round bars that fit into holes in the panel and substrate.
   B. Tooled-rod anchors are similar to rod anchors, with the addition of a tooled end to resist pullout.
   C. Strap anchors are basically flat bars that fit into slots in the substrate and panel. The shape of a strap anchor must be maintained in service; this shape can be affected by point loading and should be evaluated in the design.
   D. Wire anchors are set into holes in the panel and a mortar pocket in the substrate.
   E. Adhesive-embedded anchors are set into angled holes in the substrate.
   F. Disk anchors, which are rarely used, are rods with a round disk that sets in a slot between panels, with the rod embedded in a hole in the substrate.
2. Dowel anchors and hairpin anchors are typically used with a precast concrete backing.
   A. Dowel anchors are set into the stone and anchorage at an angle and inserted into holes with epoxy.
   B. Hairpin anchors are bent and held in place by the shape of the anchor itself. These anchors are also set into the dimension stone at an angle.
3. For repair, through-bolt fasteners, expansion anchors, or epoxy

anchors can be used. Anchorage can be countersunk and covered with a stone cap to hide the anchorage.
4. Liners are pieces of metal or stone shop-installed to transfer loads between the panel and anchorage.

Other publications from the MIA preceded the *Dimension Stone Design Manual:* the *American Standard Specifications for Interior and Exterior Marble* and the *Marble Engineering Handbook.* Before 1971, when the first *Manual* was published, one of the leading design guides for stone veneer was the *American Standard Specifications for Thin Exterior Marble Veneer* (veneer two inches and less in thickness), published in 1955 by the MIA. This guideline was produced by the membership, including quarriers, importers, wholesalers, finishers, and contractors of marble.

Standard thickness for marble is listed in the 1955 MIA *Manual* as seven-eighths-in, 1¼ in, 1½ in, and 2 in thick. Depending on the thickness, the joints were specified as butted, filled solidly with an elastic material, or filled with cement lime mortar. The joints between the marble panels were weightbearing, and plastic or aluminum cushions were required to keep the required joint spacing. Horizontal expansion joints were required at every other story height, and vertical expansion joints were required at about every 20 ft. The joint was then filled with a backer rod (cotton rope, sponge rubber, or plastic, for example) and then preferably covered with a synthetic, rubber-base caulking compound. Load-bearing spacers might be provided in the vertical joints to prevent squeezing out of joint compound. Panels were to be supported by shelf angles at every level, at all openings, and at least 20 ft in the vertical direction. The following recommendations were given for the number of required anchors for each panel:

- Two anchors per panel up to 2-sq-ft area
- Four anchors per panel up to 20-sq-ft area
- Two anchors per additional 10-sq-ft area

Flashing was installed and provided by the general contractor. The only guidance given was that "a completely waterproof installation must be provided." Various additional recommendations were given based on the type of system used:

- Type A – veneer set against prebuilt masonry wall
- Type B – veneer set against masonry wall setting simultaneously
- Type C – veneer against reinforced concrete or masonry wall

Depending on the type used, the following were some recommended practices:

- Anchors of stainless steel, brass, bronze, medium-hard drawn copper, or other noncorrodible metal at least one-eighth in thick
- Back-up material coated with dampproofing or waterproofing paint
- Solid grouting of veneer between backup and marble
- Anchorage hooked into holes in the edge of panels and holes filled with cement mortar and set into the backup system using cement mortar set into pockets

Figure 4 shows a wire tie set into a hole in the marble panel and then set into the backup system using a grout pocket. The photo was taken for an office building in Houston, TX, constructed in the 1960s and now experiencing hysteresis.

Allowable stress design (ASD) is used for marble veneer with safety factors coming from the MIA *Manual.* A safety factor of 5.0 should be used for wind loading. A safety factor of 10.0 should be used for point loads. While ASD is used for the stone itself, appropriate codes and design methods should be consulted for backup materials and connecting elements. Finally, expansion joints are to be installed vertically and horizontally at 20-ft intervals and horizontally below shelf angles.

DETERIORATION MECHANISMS

Marble (and stone itself) is seen as an eternal material, able to withstand the forces of nature throughout time and to outlive generations. We are now pushing the limits of stone, and with ever-decreasing thickness and weight of stone used, we must design and be aware of the forces that cause deterioration in a marble façade. Though a system may be properly designed, modern systems are no longer intended to even outlast a single generation without some maintenance.

In an exterior environment, marble is exposed to certain elements that will cause its decay. Durability, "the quality of a material to resist wear and decay and continue to be useful after an extended period of time and usage" (Jimenez, 2009), is an important property when dealing with a marble façade. The weathering of a stone (the wear and decay suffered) is important today because of the thickness of the stone used in modern construction. Now that panels have become thin, the loss of less than a centimeter of thickness can become significant. Weathering is associated with four factors:

- Natural defects in the materials
- Workmanship

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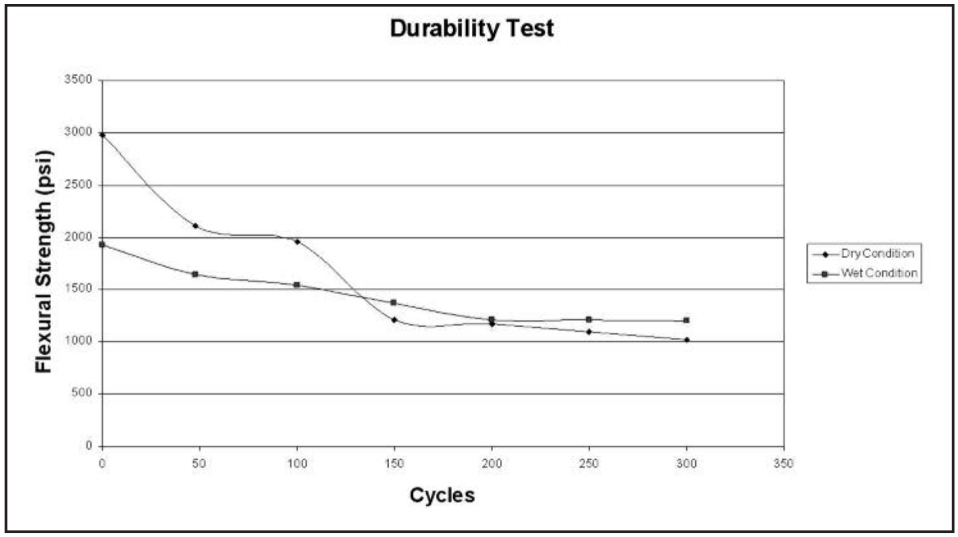
- Design
- Environment

Durability testing has been a focus of many studies in the U.S. and abroad, and a formal method to test the durability of a natural stone has yet to be accepted. However, many have accepted the following testing method:

- ASTM C880 is performed to determine the flexural strength before, during, and after a specific number of weathering cycles.
- Acid rain is simulated in this test by immersing the panels in sulfurous acid.



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A graph of a durability test for limestone using this modified test procedure is shown in *Figure 5*. What is important to take away from this graph is the trend in the testing showing a loss in flexural strength with increasing number of weathering cycles. The greatest losses tend to be in the first 50 weathering cycles. While this testing was done for limestone, similar results have been reported for marble. Jimenez has reported a 53.8% loss in compressive strength in marble after weathering testing.[6]

While all four of these weathering factors contribute to the weathering of stone, natural defects in the material tend to be the most damaging and have been the most-observed cause of problems in marble façades. Veining of a panel can be of importance, but hysteresis tends to be the most damaging.

Hysteresis

Marble is a brittle material that will exhibit some plastic behavior over long periods of time. Although eccentric and unanticipated loads can certainly cause deformation in marble panels, certain types of marble are also subject to some irreversible material expansion in the presence of thermal and, rarely, hygric forces, usually causing deformation in the form of "cupping" or "pillowing" of the panels. This intergranular, microscopic expansion, called hysteresis, is most severe in thin-stone panels and is well documented as a common cause of panel failure in marble veneers.

Certain marbles, including some coarse-grained and highly crystalline limestones marketed under the name of marbles, are more susceptible to hysteresis than others. Calcite, the main mineral component of marble, expands in the presence of heat and moisture. Calcite is anisotropic, meaning that it expands more in one direction than another. With several cycles of thermal expansion and contraction, as much as one-fifth of the initial expansion can be expected to be irreversible, causing intergranular fracturing, weakening the marble's flexural strength, and increasing the overall porosity. Because of the uneven exposure of a marble panel on a building's exterior, thermal hysteresis will eventually cause the panel to deform into a cupped or bowed shape (*Figure 6*) and may reduce the flexural strength of the stone by as much as 70%.

The effects of hysteresis have been well documented with over a century of material research. Studies seem to indicate that impurities, grain size, veining, and other obvious orientation of the stone crystals increase a stone's susceptibility to hysteretic behavior. Unfortunately, the potential for hysteresis in any one particular marble is difficult if not somewhat impossible to predict, unless empirical evidence is available. The effectiveness of using laboratory techniques such as accelerated weathering and strength testing to anticipate hysteresis has not been firmly established. Likewise, empirical evidence can also be contradictory; many thin-stone veneers using both Carrara and Georgia White marble have been observed to experience severe hysteresis, while other examples of comparable age and exposure appear to experience no hysteresis at all.

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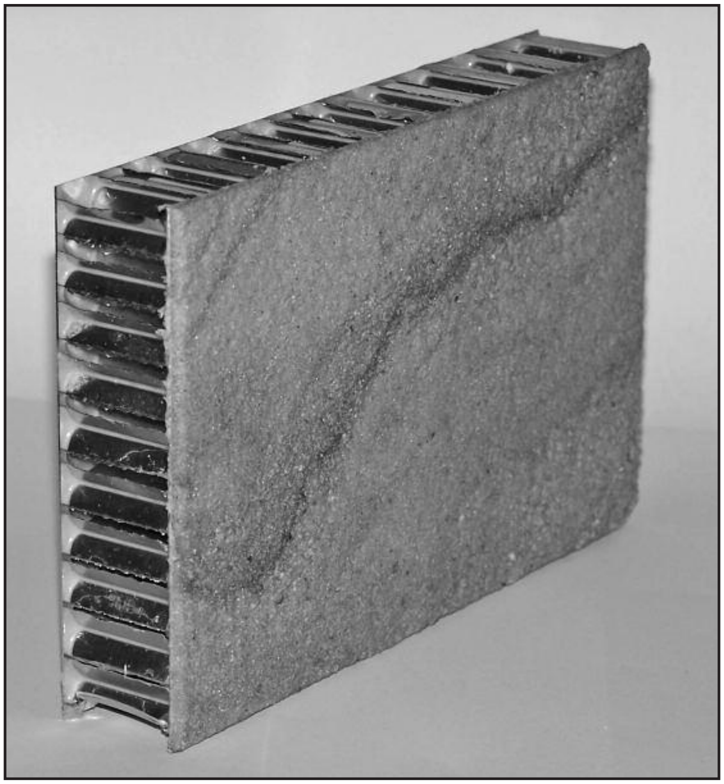
Marble Cladding Without Hysteresis

Since the potential for hysteresis is unknown in a specific type of marble, how is a designer to specify marble with such an unknown condition? If a certain marble has never been introduced to a specific area, can it in good practice be done by a designer? Unfortunately, there are no simple answers to these questions. However, as was mentioned in the previous section, empirical evidence is an excellent indicator of a specific marble's susceptibility to hysteresis in a certain area. Empirical evidence may also be given in the form of a new system that has been proven, as in the case of honeycombed aluminum backing described below. Research should be done before a project to determine the successful systems that have been used in an area. This will minimize the cost to determine the marble and system that should be used on a specific building. Below are three examples of systems and projects and are samples of the type of data required. While the data listed here are not sufficient for all conclusions about the system, these types of projects should be researched further to give historical precedent:



- In the "late 1980s, stone-faced composite panels with 5-mm-thick stone panels adhered to 4-cm honeycombed aluminum, fiberglass, or sheet steel core began to be used."[7] *Figure 7* (image from Flexistone) shows a sample of honeycomb-backed sandstone similar to that used for marble. These mechanical systems have been used successfully with marble panels.
- Prebowing of panels has also been a technique used in a building in Karjaa (west of Helsinki). This was done by sandblasting the backside of the panel until a 4-mm bowing of the panel was present. The backup of this prebowed system was concrete. As the concrete dried and shrank, the panel straightened out with it.
- The General Motors (GM) building in New York City has to date not experienced any signs of thermal hysteresis. This building was constructed in 1968 using Georgia White marble attached to precast concrete panels.

EVALUATION

It sometimes takes tragedy to bring needed change to a building code. Such is the case with the evaluation of marble façades. On October 22, 1974, glazed tile fell from a 17-story structure in Chicago, killing a pedestrian below.[8] In 1975, the city began cursory inspections of more than 2,400 buildings. From this, the city noted that observations from the ground were insufficient for finding loose panels and recommended the use of scaffolding to reveal loose sections. The first ordinance was adopted on September 13, 1978, in Chicago. Buildings of five stories or more required an up-close inspection every 10 years. Buildings older than 35 years required up-close observation every five years. In 1979, the ordinance was rescinded, and it was not until incidents in 1994 that a façade ordinance would again be in place.

Currently, façade ordinances have been enacted in Boston, Chicago, Columbus, Detroit, Milwaukee, New York, Pittsburgh, and St. Louis. Chicago's current façade ordinance was enacted in 1996, with a major revision in 2007.[9] These façade ordinances are an excellent reference and can be compared and used with judgment in areas that do not have façade ordinances already in place. One of the most important points to be taken from these façade ordinances is that up-close visual observations are required of all marble façades throughout the life of a building. Based on our experience, we recommend the following evaluation protocol.

Document Review

As with any structural evaluation, a document review should be the first step in the evaluation. Original structural, architectural, and shop drawings; repair documents; and specifications should be reviewed prior to going on site for evaluation. Information on the backup materials, anchorage, panel dimensions, moisture control, and movement joints can reduce time in the field review. Deficiencies may be in the original design, so the original drawings are invaluable in the evaluation.

Up-close Observations

Once a document review has been completed, all marble panels should be viewed up-close. This up-close observation should be performed by a licensed structural engineer or under the direct supervision of a licensed structural engineer. In this initial observation, an engineer requires only the most basic of tools (hammer, knife, level, camera, etc.). The person performing this up-close observation should look for the following:

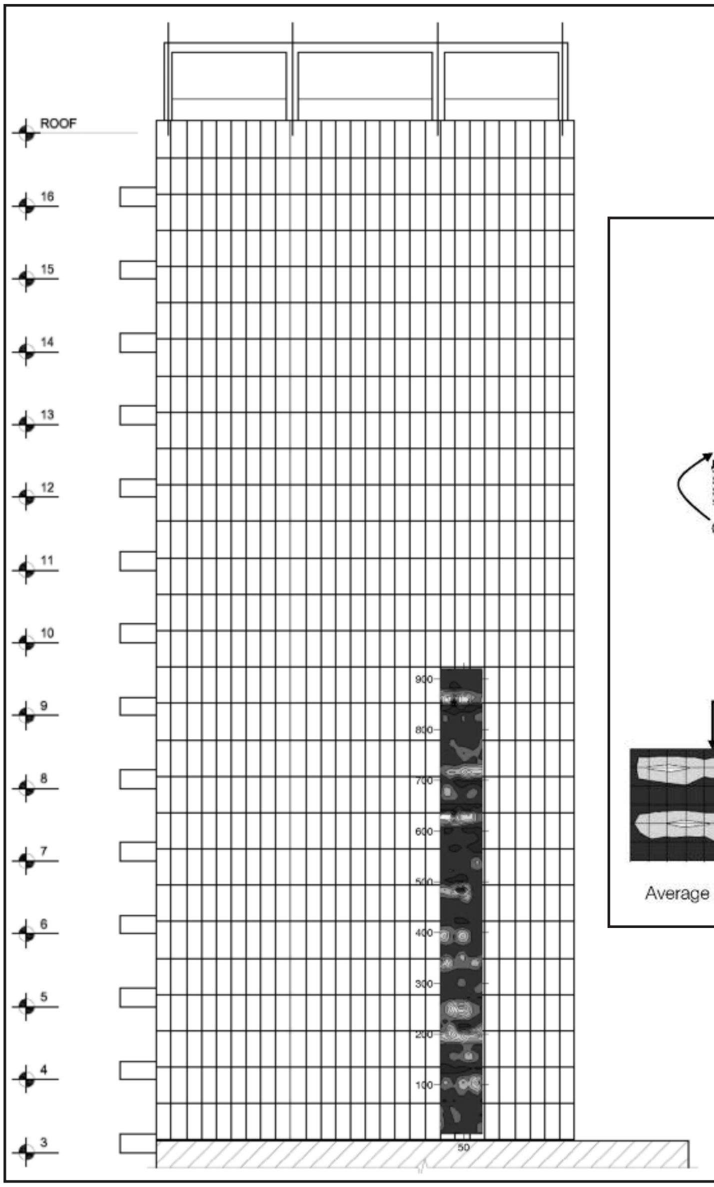
- Cracking of stone, especially at anchor location
- Staining
- Cracked, squeezed, or stiff sealant
- Bowing of panels
- Spalling at anchors
- Loose panels
- Previous repairs, removed signage, or other attachment
- Movement
- Structural defects

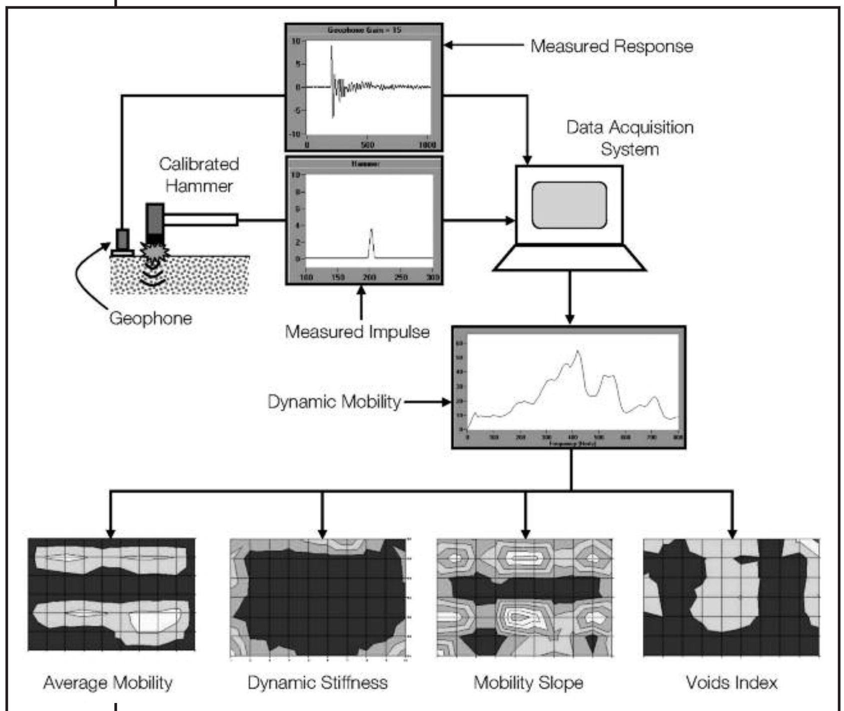
All observations should be noted on an elevation of the building. These field notes will be used later to create graphic output useful in determining a course of action.

Nondestructive Evaluation (NDE)

Once this initial observation is complete, nondestructive testing can be used to give further system information, including relative stiffness at anchorage points, location of the anchorage, and construction of the system. The following NDE methods can be useful in evaluating a marble façade:

- Boroscope – A nondestructive evaluation tool with rigid or flexible opti-





cal tubes that allow visual observations of concealed conditions inside wall cavities.

- Impulse response – A nondestructive technique that can be used to qualitatively evaluate the integrity of marble panel elements and their connections
- Ferroscan – A system that can be used to detect metal within a wall cavity. Wire ties, metal clips, and shims are able to be located.
- Photographic magnification
- Remote observation
- Ground-penetrating radar (GPR) – A tool used to detect metal within a wall, it gives more detailed information than a Ferroscan, is more expensive, and requires operator training to accurately determine results.
- Infrared thermography – Can be used to determine water/air leakage in a wall system.

Based on the results of the dynamic mobility measured by impulse response testing, the dynamic stiffness and average mobility of the panels being considered can be plotted on contour maps to discern patterns in the support conditions of the panels (*Figure 8*). Localized regions of relatively high stiffness generally coincide with vertical support attachment locations. See *Figure 9* for a sketch and sample results from impulse response testing.

MATERIAL TESTING

In addition to *in-situ* testing, material testing should be done on failed panels as well as panels performing well and panels not in service (unused panels in storage, for instance). It has been debated whether or not the laboratory testing correctly simulates natural weathering conditions. Based on our experience, it is recommended that rather than solely relying on material testing, a historical precedent should also exist for a particular stone in a particular region to give information on anticipated performance. Three types of material testing can be done:

- Petrographic (petrology)
- Chemical (lithogeochemistry)
- Physical

Petrology involves cutting thin sheets (20 to 30 microns) of stone to view the minerals under a microscope. Since this testing method is somewhat subjective, it is recommended that chemical testing be performed to compare with results from petrology testing. X-ray diffraction (XRD) analysis is another available method of petrology that has been in use for decades.

Lithogeochemistry is a chemical analysis of stone, including, but not limited to, the following tests:[10]

- Instrumental neutron activation analysis (INAA)
- Atomic absorption spectroscopy (AAS)
- Inductively coupled plasma emission spectroscopy (ICP-OES)
- X-ray fluorescence spectroscopy (XFS)
- Inductively coupled plasma emission mass spectrometry (ICP-MS)

Physical testing can involve a number of tests, including compressive strength testing (ASTM C170-90), flexural testing (ASTM C880-98), and modulus of rupture testing (ASTM C99-87).

Additional information on testing:

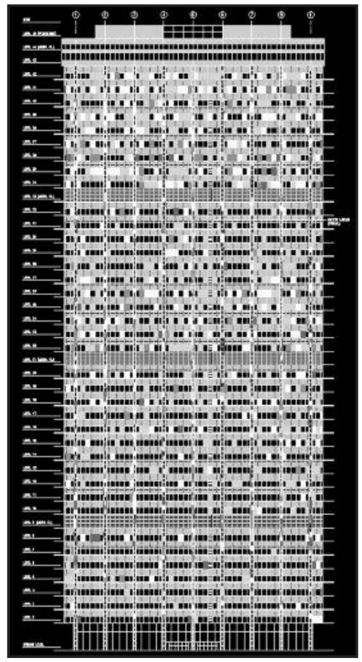
- Stone is a natural material, and properties will vary within the same quarry. It has been recommended by Farmer[11] that testing for stone properties be conducted for every quarry block to ensure that specifications are met.
- The strength of a stone may vary from wet to dry conditions, so it may also be recommended that standard tests be conducted in a wet (soaked at 22°C for 48 hours) condition.
- The rift in a stone is the plane in which cracking will most easily occur. Testing may be required parallel and perpendicular to the rift.
- Water absorption measures the porosity of a stone and will indicate the susceptibility of a stone to incur damage during freeze/thaw cycles. Water absorption is listed as a percentage change in weight by soaking the stone for 48 hours. Marble has a limit of 0.20% change in weight. Note that testing is required of a 2-in specimen, and a thinner specimen may give results showing higher water absorption.

GRAPHIC PRESENTATION

After a field survey is completed, areas of façade distress can be converted into a color-coded map to visually understand the damage and to assist an owner in determining repair priority. Criteria should be decided upon that will be used in creating this color-coded elevation. Several key components in the system should be assigned damage levels from "no damage" to "replacement." In a marble façade, the following are typically observed in a field survey and can be included in a color-coded elevation:

- Cracking of marble
- Corrosion of anchorage
- Sealant condition
- Shelf angle condition

A sample color-coding system developed by the authors is shown in *Figure 10*. Using this scheme, each panel is given a color based on the criteria listed in the color-coding system. If any part of the system affecting a specific panel requires immediate replacement, the entire panel is colored, showing the owner a need for action. *Figure 11* shows a sample of a façade that has been color coded for deterioration. [Editor's note: Unfortunately, we are printing in black and white.]



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REPAIR

Once an evaluation and understanding of the possible cause(s) of deterioration is (are) completed for a marble façade, its repair may begin. Results from panel and anchorage testing will give information on the ability of both the panel and anchorage to resist the given loads. Options should be compared for temporarily stabilizing the panels or installing protection for pedestrians below.

Conceptual steps in stone façade repair:

- Remove all loose panels from the building and install waterproofing on the backup material where panels have been removed.
- Temporarily stabilize all panels where the strength of the panel or strength of the connections is in question.
- Install pedestrian protection if temporary stabilization is not installed, but the strength of the panel or the strength of the anchorage is in question.
- Replace all marble panels on the façade.

Temporary stabilization will support bowing marble panels that have lost some support from the original anchorage. The panels experiencing hysteresis will continue to bow as long as they are exposed to the same environment under the same conditions. The life of this temporary stabilization is dependent upon the rate of bowing.

Several solutions for mechanical stabilization have been used in practice by others. Stainless steel straps across the length of a panel attached with bolts were used on the 80-story Amoco tower in Chicago, Illinois. Additional mechanical treatments have been attempted with unsuccessful results in a laboratory, including fiber-reinforced polymer (FRP) and polypropylene honeycomb backing.

Typically, we have used postinstalled adhesive anchors to attach panels to the substrate. Using adhesive anchors instead of mechanical anchors will minimize cracking, since the adhesive anchors do not require torque during installation. Coring through a panel may cause damage, and mock-ups should be created before large-scale panel stabilization is attempted.

In an area where a façade ordinance does not require maintenance, an owner may leave these temporary anchors in place longer than the anchors should be used. To force an owner to continue repair and maintenance on a façade experiencing hysteresis, we have used wood blocking between the head of the anchor and the face of the marble. As this wood blocking deteriorates in the weather, panels will again become loose and an owner will need to have the façade looked at again by an engineer. This wood blocking should be able to deteriorate before further deterioration occurs in the panel and anchorage system.

Not all panels require temporary stabilization. Depending on the observed deteri-

Color	Cracking	Corrosion (anchorage)	Sealant	Shelf Angle
Green	No obvious damage	No obvious damage	No obvious damage	No obvious damage
Yellow	Hairline cracks	Localized corrosion	Hairline cracks	Localized corrosion
Orange	Chipping, spalling	Significant corrosion	Adhesion, cohesion failure	Significant corrosion
Red	Remove panel	Remove panel	Sealant removal	Shelf angle removal

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oration, only certain panels need to be stabilized. The graphic presentation is useful in this step of stabilization. Rather than going through lists of data on the façade, the engineer can isolate and deal with the most relatively severe locations.

It should be noted that no mechanical method of stabilization has been shown to be a permanent solution to hysteresis. The only way to stop hysteresis is to remove the element causing the hysteresis or to change the material. Over time, the strength loss of panels experiencing hysteresis will continue. The eventual solution is panel replacement in kind or with a different material.

For a façade experiencing hysteresis, 100% panel replacement will eventually be necessary. Balancing safety and budget should be coordinated between the engineer and the owner. Panels that cannot be stabilized due to the extent of deterioration must be removed immediately. Waterproofing is then installed over the areas where panels have been removed. *Figure 12* shows a mock-up of waterproofing to be installed over a backup material. In some cases, the mastic in the backup system contains asbestos, and the area is not able to be ground smooth without asbestos abatement. In this instance, it was decided that peel-and-stick waterproofing should be applied rather than coating applied by roller. The surface roughness of the backup material is apparent through the peel-and-stick waterproofing, but, in this case, the solution was the most appropriate given the time frame before the building's scheduled demolition. For many façades experiencing hysteresis, asbestos may be present due to the building's age, and testing should be performed before repairs are recommended.

Now that temporary stabilization is in place and certain panels are removed, the plan to achieve panel replacement must be decided. More panels may require temporary stabilization within the year. Additional panels may also require removal in the same time frame. The rate of hysteresis is not known, hence the need for frequent up-close observations.

A repair program can take years to implement. It is not typical for an owner to immediately replace all marble panels on a façade. Even a 20-story building partially clad in marble can cost upwards of $10 million for total panel replacement. An owner may stage construction, and will need an engineer's input on the need for panel replacement.

MAINTENANCE

Once construction of a new marble façade is complete, if an aging façade has never received an up-close observation or if repairs have been completed, a maintenance program should be put into place. The questions arise: What needs to be done and how often? Where can an engineer go for further information about requirements? What do building codes have to say about maintenance?

According to Chapter 34 of the IBC, buildings must be maintained by the owner in a safe condition. There is, however, no reference to façade maintenance. The MIA has a "maintenance of exterior stone" section. This section states that "normal maintenance should include periodic inspection of stone surfaces for structural defects, movement, deterioration, or staining."[12] How is periodic inspection defined? Does this mean an up-close inspection? What should the frequency be?

The IBC and the MIA *Manual* may not have much to say about the details of façade maintenance; but ordinances, guidelines, and other publications do give a starting point for maintaining a marble façade. These references include:

- Façade ordinances (Chicago and New York, notably)
- ASTM STP 1444
- ASTM E2270-05
- Publications in technical journals, conference proceedings, etc.

Façade ordinances vary on which buildings require up-close evaluation; but a common requirement is that, for all buildings that are 80 ft or six stories high, a program of up-close evaluations should be implemented. The following are general recommendations for buildings that are performing well, regardless of height:

- All sealant on a marble façade should be replaced every 15 to 20 years.
- Mortar joints should be repointed every 20 to 25 years.

Up-Close Observations

Due to the nature of thin-marble panels and the haste with which many were constructed, up-close observations are required for all marble façades, regardless of age. Even when a façade is not known to be experiencing problems, up-close observations of a façade should be conducted at regular intervals. Façade ordinances vary from city to city and require that 25% - 100% of the area of each elevation be observed during an up-close evaluation. The frequency of the up-close observations for a marble façade will vary, depending on the corrosion potential of the anchorage

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and the presence of flashing. Different façade ordinances require observation of a façade every 1 - 12 years. An architect trained in façade evaluation is also able to perform this assessment, though a structural engineer knowledgeable in façade assessment will need to be consulted if any problems are found.

Based on façade ordinance review and experience, it is recommended that a 100% review of a marble façade be conducted at least every four years during a building's life. If a building has an unknown substrate, unknown anchorage, or is at least 50 years old, an exploratory opening should be made at a minimum of one location per elevation. After a significant wind or seismic event, up-close visual observations should be performed.

Frequency of Observations

The ASTM STP 1444 provision[13] indicates the following: "Frequent inspections and evaluations are recommended to ensure that any deficiencies or maintenance needs are identified prior to the conditions becoming severe or a safety concern." This is recommended as a proactive measure for owners. The author of this provision recommended semiannual partial visual inspections during changes in the seasons and biennial, up-close observations of 100% of the façade.

Based on the current literature and the authors' experience, a façade that is experiencing hysteresis requires full up-close observation every one to two years. This time frame is highly dependent on the type of stone, project location, and extent of deterioration. Engineering judgement should be used in determining the frequency of observations for a particular project.

CONCLUSION

Thin-marble veneer has been used on building façades since the mid-twentieth century. The popularity of marble façades preceded understanding of the technology. Engineers, architects, and owners are beginning to recognize the growing need for up-close observations on marble façades because of the nature of the material and the lack of understanding of the design of many currently existing systems. Using visual, nondestructive, and destructive techniques, owners and engineers are able to determine a future course of action for an existing marble façade. Owners and engineers should be informed about options with an existing façade experiencing hysteresis and requiring 100% façade replacement. With proper evaluation, repair, and maintenance, façades experiencing hysteresis can be given a repair scheme that is both good for the owner and safe for the public.

FOOTNOTES

1. Patrick Loughran, *Failed Stone*, Burkhäuser, Basel, 2007.
2. Ibid.
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4. *Dimension Stone Design Manual, Edition VI*, Marble Institute of America, Cleveland, OH, 2003.
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6. Gabriel A. Jimenez, "Durability Aspects in the Design of Masonry Stone Façades," *Concrete Repair Bulletin*, May/June 2009.
7. Loughran, p. 20-21.
8. I.R. Chin and H. Gerberding, "Evolution of the Development of the Chicago Façade Inspection Ordinance," Building Façade Maintenance, Repair, and Inspection, ASTM STP 1444, J. Erdly and T. Schwartz, eds., ASTM International, West Conshohocken, PA, 2004.
9. Municipal Code of Chicago, Section 13-196-031 through 13-196-039, City of Chicago, Department of Buildings, 120 N. Racine, Chicago, IL 60607.
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11. M.C. Farmer, "Unique Considerations for Stone Façade Inspection and Assessment," *Building Façade Maintenance, Repair, and Inspection*, ASTM STP 1444, J. Erdly and T.A. Schwartz, Eds., ASTM International, West Conshohocken, PA, 2004.
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