Design Issues for Thin-Stone Cladding Systems

By Edward A. Gerns

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INTRODUCTION

Stone has been used as a building material for thousands of years. Its aesthetics and sense of permanence have made it a popular material, especially among builders and architects. Many of the significant buildings throughout history have been constructed of stone. The evolution of stone facades closely parallels the evolution of building construction and technologies. Economics and alternative building systems have led to numerous variations in the installation of stone on building facades over the past 100 years. A complete understanding of the material and installation techniques is critical for the proper design and installation of thin-stone cladding systems.

Numerous innovations in thin-stone cladding systems have occurred over the past 20 years. Failures of the older systems have provided valuable insight into the design approach of newer systems. This paper will provide an overview of the use of stone in construction with particular emphasis on recent developments in the evolution of thin-stone facade cladding systems.

HISTORY

Historically, stone was used for both decorative and functional purposes. With few exceptions, building systems incorporate inexpensive backup materials in combination with more expensive facing. Early stone structures were typically solid, multi-wythe, load-bearing assemblies combining high quality facing stone finished to very tight tolerances with a looser rubble or brick backup.

In the past 150 years, advances in technology and the introduction of new building systems have changed how stone is incorporated into building systems. A brief overview of the historical use of stone is important to understand how economics and technology have contributed to the remarkable changes in the use of stone.

The most dramatic change in building construction was the result of the industrial revolution of the 19th century. The development of new industrial processes facilitated the economical production of metal shapes that led to the development of the skeleton frame structural system. This system enabled the exterior wall to be used as a non load-bearing component of the building. As a result, the structural function of the exterior facade was no longer necessary. The facade could be treated as a skin that wrapped the skeletal frame. The skin still needed to transfer wind loads to the frame, but it was no longer required to support interior floor loads.

Early skeletal frame buildings used numerous exterior cladding materials. Brick, terra cotta, and stone were all used, with economics frequently dictating both the location and quantity of the materials. Stone, still a relatively expensive cladding material, was frequently used only on the lower floors and the interiors of high-rise structures. Early methods of anchoring the exterior cladding were varied and frequently experimental.

The building boom of the early 20th century and the associated dramatic increase in building heights resulted in the need for increased economies of materials. Early skyscrapers tended to use primarily brick and other smaller unit-type materials, but by the 1920s larger limestone slabs began to be used with greater frequency. Many of the buildings of the 1920s and 1930s were clad with granite or marble on the lower stories and limestone panels on the higher portions of the facade. The uniformity of appearance of the limestone reinforced the architectural aesthetic of the Art Deco massing while the richness of the color and veining of the granite and marble accentuated the desire for human scale at the base of the buildings. The limestone panels were typically at least 4 inches (10 cm.) thick. During this time and until the 1950s, each floor was typically designed individually with panels stacked vertically between supports near the floor levels and horizontal movement joints installed directly below the support or at mid-story.

With the development of curtain wall systems and the rise of modernism in the 1950s, stone began to be used as a thin panel within lightweight curtain wall or facade systems. The stone panels were arranged in vertical bands as column covers or in horizontal strips as spandrel panels. Numerous techniques were employed to support the stone panels, both within curtain walls as well as individually.

The 1960s and 1970s brought the development of composite systems that included stone-faced precast concrete panels. The stone facing generally ranged between 3/4 in. and 1-1/4 in. (2 cm. and 3 cm.) thick on these type systems. The rise of prefabrication during this period also led to numerous truss-type systems in which the stone panels were mounted to steel trusses or frames in a shop and then transported to the site for erection on the building.

By the late 1970s, the resurgence in popularity of stone, corresponding with the popularity of the post-modern style of architecture, resulted in dramatic increases in the use of stone as an exterior cladding material. The material was still relatively expensive; thus, designers experimented with systems utilizing stone as thin as 1/4 in. (6 mm) in composite panels. Numerous support systems, many of which were developed by the stone fabricators, were also available. Panelized strong-back type systems became widely used because they facilitated a rapid installation.

Today, numerous systems are available for installing stone on the exterior of buildings. Many factors must be considered by the designer in both the design and detailing of stone support systems to prevent premature failure and to ensure long-term durability. Lessons learned from investigation of older, thin-stone clad building provide valuable knowledge in both the design and restoration of thin-stone clad buildings.

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STONE TYPES

Unlike manufactured materials used in construction, the physical characteristics vary greatly between geologically different stones as well as between stones of the same type. These variations contribute to the inherent beauty of stone as well as its potentially varied physical characteristics. Stone, used in building construction, is categorized as one of the following types:

Sedimentary

These include limestone, sandstone, brownstone, and shale. This type of stone is the product of deposits of sediment materials in prehistoric river and lake beds. The sediment is the result of decomposition and erosion of other rocks, minerals, and organic matter that are bonded together through compaction and naturally created cementitious products. Distinct bedding planes between individual layers of material and grain size characterize sedimentary stone.

To minimize accelerated deterioration of sedimentary panels, the individual pieces should be fabricated such that the orientation of the bedding planes remains consistent with the natural bedding or the orientation in which stone was geologically formed (*Figure 1*).

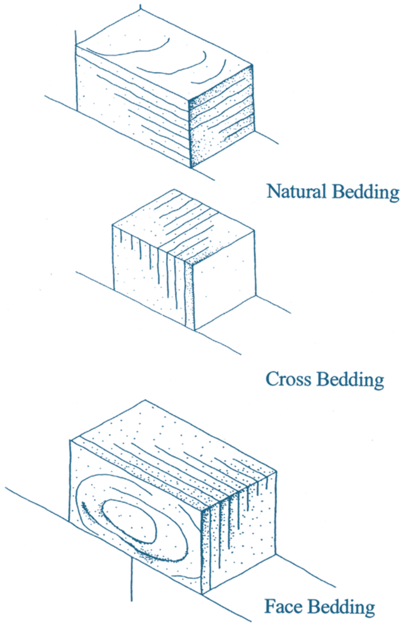

Figure 1 - Examples of bedding plane orientation.

Igneous

These include granite and schist. This type of stone is the result of volcanic activity and the consolidation of molten magma. Igneous rock typically contains quartz, the crystal form of silica. Classifications of igneous rocks are based on the silica content within the stone.

The finishes used on igneous panels, particularly granite, can have a significant architectural as well as structural impact on the design of the system. Various finish techniques such as flame finish, bush hammering, and other abrasive treatments can introduce microcracking into the exterior face of the stone. Microscope evaluations have shown cracking as deep as 1/8 to 1/4 in. (3 mm to 6 mm) depending on the treatment. For a panel that may only be 1-1/4 in. (3 cm) thick, the loss of effective thickness of 1/4 in. (6 mm) is significant and must be considered. These specialized surfaces also increase susceptibility to freeze-thaw damage and similar deterioration due to the increased surface area.

Metamorphic

These include marble and slate. Metamorphic stones are the result of sedimentary or igneous stone being subjected to millions of years of heat and pressure, resulting in a recrystalization of pre-existing rock. Two types of metamorphic processes can occur to change rock. The first is thermal, where rock is subjected to prolonged exposure to heat in a confined environment. This is the process by which limestone is converted to marble. The second process is regional metamorphism and is associated with the creation of mountains where rock is subject to extended periods of stress or pressure. During this process, the recrystalization of the stone results in new rock particles forming parallel to the pressure. Slate is the most commonly used example of this type of stone. Metamorphic rocks are categorized based on the pre-metamorphosed rock. Because of the grain structure of metamorphic rock, it is susceptible to a phenomenon known as hysterisis (*Figure 2*). As the exposed surface of the panels experiences heat, it will expand differently than the unexposed surface. As the exposed surface cools, the interlocking grain structure does not return to its original position. Thus, a permanent elongation of the exposed surface occurs. Repeated cycles of heating and cooling will result in a permanent bowing of the panels. The magnitude of bowing is related to the support conditions and panel thickness.

Because stone is not a man-made product, its physical and aesthetic characteristics can vary significantly even within the same quarry. These unique features of stone include:

1. Natural planes of weakness, such as cleavage planes, bedding planes, and rifts occur within any quarry. These features are discontinuities within the matrix of the stone.
2. The physical properties of an individual stone will also vary depending on whether it is tested in a wet or dry condition.
3. Stone is also not an isotropic material; therefore, its strength will vary depending on the orientation of load.
4. Stone is a heterogeneous material, which also contributes to variability.

Stone within each of the geologic categories has distinct physical characteristics. Within the last 30 years, the fabricators and the stone distributors have established test procedures and minimum standards for material properties. Historically, however, stones were used as very compact shapes that were subjected primarily to compressive forces. The building as a whole was massive enough that lateral loading on individual components

Figure 2 - Representative example of hysterisis.

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was not an issue, since the lateral loading was resisted by the geometry of the structure rather than individual components. The transition from stone claddings systems designed as load-bearing masonry structures to individually supported stone panels was not smooth and uniform. Early stone cladding systems relied on empirical techniques rather than known material properties.

Traditionally recognized stone properties include compressive, flexural, shear, and tensile strengths; density, abrasion resistance, coefficient of thermal expansion, and modulus of elasticity. In addition to these established properties, other properties that are frequently overlooked can contribute to premature failure of a stone cladding system. These properties include permanent volume change or hysteresis, freeze-thaw weathering, chemical weathering, thermal weathering, effects of stone finish, and permeability. Simply stated, these properties may reduce the strength properties of the particular stone. The effect will vary depending on the type of stone.

EVOLUTION OF INSTALLATION SYSTEMS

The early thin stone anchorage systems typically used carbon steel or galvanized steel shelf angles anchored at each floor to support the stone cladding. The panel directly above the shelf angle was notched to accommodate the thickness of the angle. Panels above the notched piece were stacked on shims up to the next support. Sealant was installed in the joints between panels, concealing and protecting the shims. Typically, the shims were lead; however, carbon steel shims were sometimes substituted. As the sealant between panels failed in these early systems, the carbon steel angles and shims would corrode. Since corrosive scale occupies a greater volume than uncorroded steel, the joints were not adequate to accommodate the scale.

An expansion joint may or may not have been included below the shelf angle supports. The lack of an expansion joint, particularly in concrete frame buildings that are subject to shrinkage and frame shortening, would often result in failure of the stone cladding due to accumulation of compressive stresses.

Lateral loads on thin stone cladding were typically resisted by brass pins set into holes drilled in the edges of the panels. The pins were secured with wire anchored to structural members or embedded into grout- or plaster-filled pockets in concrete systems. This method of attachment was common in interior applications, but was occasionally used in exterior applications. Other systems utilized a bent plate with the outstanding leg fit into the joint between adjacent stones. A pin inserted through a hole in the plate extended into holes drilled into the edge of the stone panels.

Inward loads, if not accommodated by a rigid lateral anchor, were frequently resolved by placing mortar or plaster spots in the cavity between the substrate and the back of the panel. Masons frequently used a gypsum-based plaster or added gypsum to the mortar to speed the setting time. Although this technique was successfully employed in many interior applications, deterioration resulted from exterior or interior applications exposed to moisture. When gypsum becomes wet, a chemical reaction occurs between the cement, gypsum, and water, resulting in Ettringite formation. The crystal structure of Ettringite occupies a volume larger than the original materials. Failures of the stone cladding frequently occurred when the mortar was confined and the expansion could not be accommodated. Calcium chloride and other salts were also sometimes added to mortar to act as an accelerator or retarder. The presence of chlorides significantly increases the corrosion of carbon steel components.

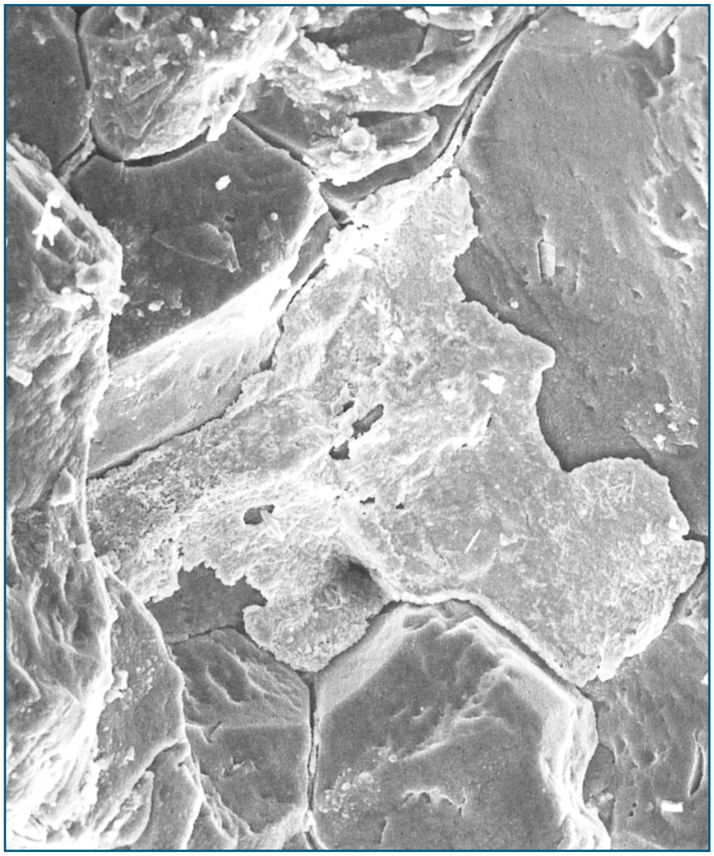

Figure 3 - Microscopic view of marble.

The 1960s also marked the rise of prefabricated systems in which the stone was anchored to a supporting system and the composite panel was attached to the structural frame of the building. The most widely used of these systems were stone-faced precast concrete panels. These panels were constructed by attaching stainless steel hairpin anchors into the back of thin stone facing panels. The stone was then laid face down in a casting bed, and the concrete backing panel was cast over the anchors. Failures of these early systems resulted from the bond between the concrete and the stone. As the concrete cured and shrank, the stone face cracked. Also, if the concrete was bonded to the stone, the differences in the coefficient of thermal expansion between the stone and concrete could cause the face panel to crack. A bond breaking material between the stone and concrete was later incorporated in composite panel design. Proper handling of the panels during fabrication, transportation, and erection was critical to prevent damage.

Within the past 10 years, lightweight composite panels have been introduced as an alternative to the more conventional precast systems. These panels consist of a very thin layer of stone, typically 1/4 in. to 3/8 in. (6 mm to 9 mm) thick, that is glued to an aluminum honeycomb substrate (*Figure 4*). These panels weigh between 3 and 4 pounds (15 and 20 kg/m2) per square foot while conventional stone panels of similar thickness weigh

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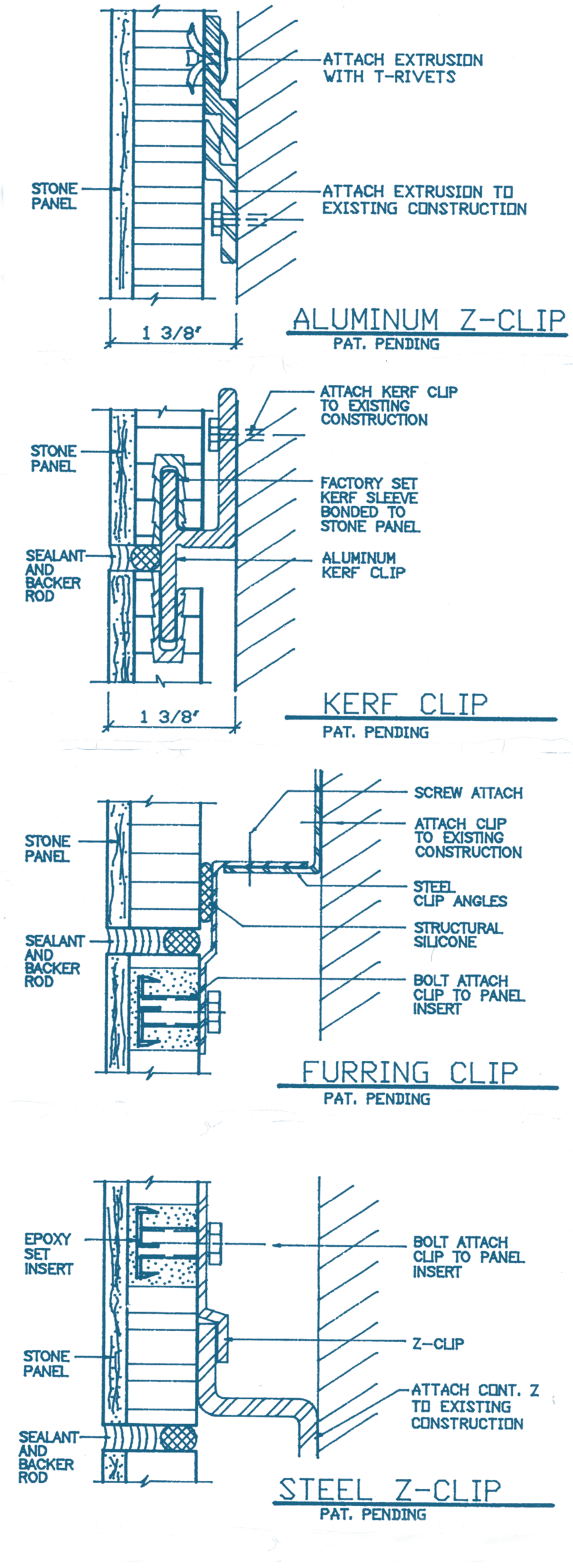

Figure 4 - Representative lateral anchorage of composite panels from product literature for Ultra-Lite Stone by Stone Panel, Inc.

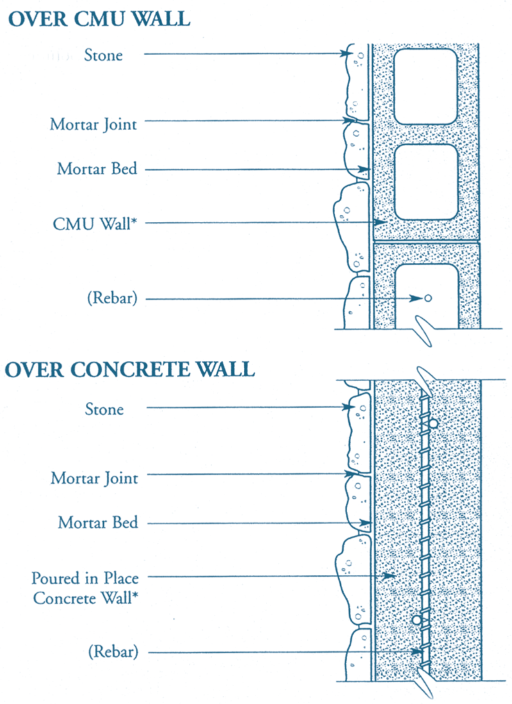

Figure 5 - Stone tile system applied to CMU and concrete substrates.

between 15 and 20 pounds (75 and 100 kg/m2). These panels offer significant cost and weight savings; however, their long-term performance remains undetermined.

Another system that has been recently developed with a limited history of use consists of adhering smaller stone tiles to a concrete, masonry, or stud wall sheathing by means of latex-modified mortars (*Figure 5*). To date, installation of this system has been limited to residential construction and small commercial applications.

STRUCTURAL DESIGN CONSIDERATIONS

The loads that are expected on the thin stone panel usually govern the thickness and (potentially) the size of cladding panels. The ability to accurately predict the expected behavior of the system is critical to the performance of the cladding system. Depending on the building location, seismic or wind loads will govern the design loads.

Depending on the type of material to be used for the panels, the stone's strength and an appropriate factor of safety can be used to select a preliminary thickness for a particular panel size. Factors of safety vary greatly, depending on the type of material to be specified. Safety factors are used to account for variations of the material, aging, load variation, and statistical predictability. The following factors of safety are generally used for flexural design of different types of stone:

Stone Type	Flexural Design Safety Factor
Granite (not at anchors)	3
Granite (at anchor locations)	4
Marble (not at anchors)	5
Marble (point loads)	10
Limestone and Sandstone	8

To speed construction and minimize field fabrication, many modern cladding systems are shop fabricated and installed with cranes

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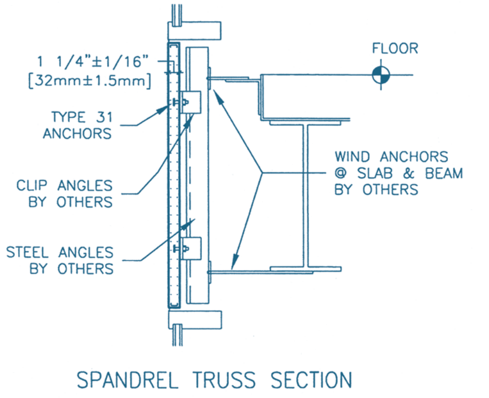
rather than being handset. Stone panels can be pre-anchored to steel truss frames as an alternative to precast panel systems (*Figure 6*). In the 1980s, non-stress proprietary anchors were introduced. These anchors transferred loads in bearing rather than friction or adhesion and are frequently used for fabrication of the steel truss systems. Because stone, like other masonry materials, is a very brittle material, consideration for differential stiffness or deflection compatibility between the stone and the support frame is critical to prevent cracking both during installation and while the system is in service.

DETAILING ISSUES

Tolerances/Constructability

Although not as significant in older load-bearing structures, tolerance is one of the most significant factors affecting thin stone cladding. Tolerances in thin stone cladding include both fabrication and construction variations, which must be accommodated within the system to ensure a proper installation. Frequently, inadequate adjustability within a cladding system can result in field modifications that may deviate from the original design intent and may compromise the performance of the system. Tolerances become more significant as the thickness of the panel decreases.

Fabrication tolerances can vary between shops. The significant tolerances for individual pieces include length, width, thickness, squareness, and locations of kerfs and holes. It is significant to note that industry-recommended tolerances are typically only possible in a shop setting. Yet field cutting of kerfs and drilling of holes is often unavoidable and is a common practice in many installations.



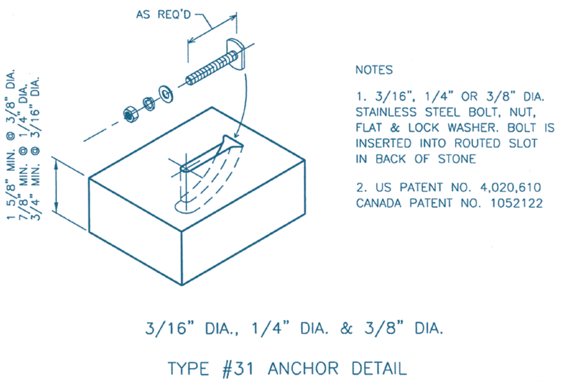


Figure 6 - Prefabricated truss system and non-stress anchor.

Installation tolerances, or the relationship between the cladding and supporting structure, can vary dramatically. Industry standards for steel and concrete frames may require as much as 5 in. (12.7 cm) of potential in/out adjustment for cladding systems on a tall structure. Vertical adjustability requirements also vary depending on the anchorage system. Vertical and horizontal adjustability is achieved through slots or shims. Again, if the system is not properly designed, excessive shimming may occur during installation. Slots are frequently detailed for adjustability; however, slots that are oriented in the direction of load are extremely installation-dependent for proper performance (*Figure 7*).

Inadequate adjustability can lead to excessive field modification of stone panels by back-checking or notching, potentially removing stone that is necessary for the connection or for the panel to properly resist design loads.

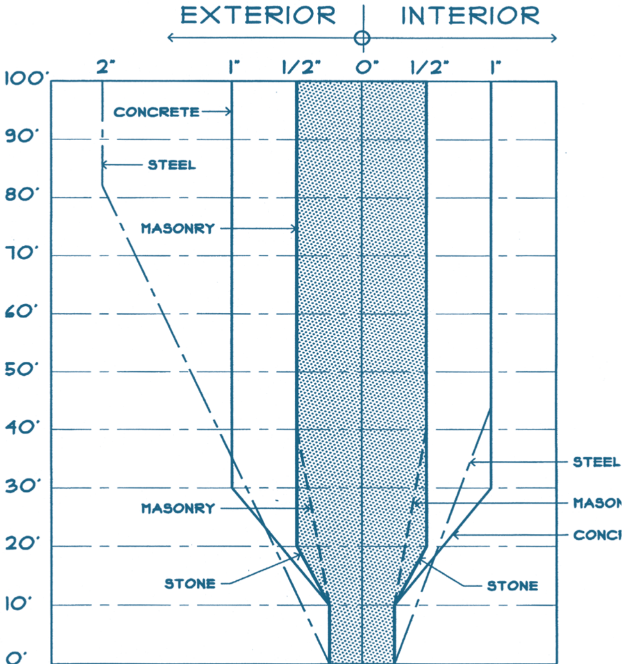


Figure 7 - Tolerance envelope for deviation from plumb.

Also related to constructability are techniques for installation of the last panel in a system or in a course of stone. These panels are typically located at corners or at the top of a building where they are subjected to the highest wind loads and have the greatest potential to compromise public safety. Frequently, the responsibility for an installation and attachment scheme is left to the contractor. The pieces may be anchored with a "blind" system or by some other improvised technique. Careful attention is necessary to provide adequate anchorage for all panels within the cladding system, not simply the "typical" detail.

Movement

Proper consideration and accommodation of all potential movement within the cladding system as well as within the structural system are necessary to prevent both local failures and system failures. Thermal, seismic, wind, creep, and shrinkage movements must be considered for individual panels as well as the entire system. Incorporation of properly designed vertical and horizontal expansion joints and proper installation of the joint are necessary to prevent failures.

Water Infiltration

One of the most fundamental issues affecting almost all exterior building components is water infiltration. Thin stone cladding systems rely on the relatively thin cladding panels and sealant between the panels as the primary line of defense against water infiltration. Obviously,

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these systems may be somewhat watertight initially, but as the sealant begins to deteriorate water will reach the underlying substrate and anchorage. A second line of defense against water infiltration should be incorporated into the design; however, it is frequently not included because of cost and installation difficulties.

Early systems frequently did not consider the effects of water penetrating the cladding system. Galvanized steel may have been used for connection components including shelf angles, lateral straps, and bolts. The rate of corrosion was greatly reduced depending on the thickness of the zinc coating. Frequently, some of these components may not have been galvanized. As the system aged, galvanized and unprotected steel would have eventually corroded and resulted in the failure of components or of the entire system. Within the past 30 years, stainless steel has been recommended for all anchorage components that are in contact with the stone.

Galvanic Corrosion

Even components with high corrosion resistance may corrode if two different metals are in contact due to galvanic corrosion in which the rate of corrosion of the less noble metal increases. Particular attention to galvanic corrosion is necessary in environments with airborne chlorides such as ocean properties or urban environments where salt is used during snow removal. As a practice, all dissimilar metals should be separated.

CONCLUSION

The use and popularity of thin stone cladding systems in the building industry will likely continue at current levels. Many of the older thin-stone systems have begun showing signs of aging and outdated design methodology. Inconsistent maintenance, neglect, and normal aging of the envelope have led to an increase in failures. Newer cladding systems installed rapidly or using unproven technologies have failed more quickly than many of the preceding installation systems. A proper understanding of the materials, design, and constructability are important to proper design of thin-stone cladding systems. ■

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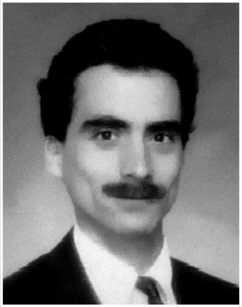
ABOUT THE AUTHOR



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COURT VERDICTS RULE FOR EIFS' VIABILITY

Despite rumors of on-going litigation, two recent Federal courts decisions have found EIFS systems victorious. Ken Schneider, AIA, RRC, principal of the Charleston-based firm of Campbell, Schneider & Associates, Architects, Engineers, Roofing & Moisture Migrations Consultants, led the defense expert witnesses in both cases. In April 2000, in the U.S. District Court in Mobile, Alabama, Attorney John Debuys of Birmingham won a case in just five hours of testimony in Oechsner v. Parex, Inc., et al. The case alleged construction defects in the Oechsner's beach-front house at Orange Beach Alabama. Oechsner is the owner of the famous Pat O'Brien's Restaurant in New Orleans. Schneider's second victory in November 2002 involved 89 EIFS-clad buildings constructed at Barksdale Air Force Base in Bossier City, Louisiana. Tried by Attorney Kathy Morgan in the U.S. District Court in Shreveport, the $22 million dollar case was brought by Roxco, Ltd, the general contractor, against Harris Specialty Chemicals, Inc. After several days of deliberation, a verdict was returned for the defendant. "These...buildings stand as an outstanding example of how well EIFS performs as a cladding," Schneider said. A third recent decision by a California Count has also exonerated Drivit, a manufacturer of EIFS systems.

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