Case Study of Stone Veneer Failure

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Abstract

The primary concerns for veneer systems are typically cosmetic (appearance) and the function as part of the building envelope, especially regarding moisture issues. However, the selection of the veneer system and the execution of the veneer support can become issues of public safety. This case study outlines issues of veneer-related safety on two public buildings with similar construction. Improper selection of the veneer materials during the design phase of the project and improper execution during the construction phase caused several safety concerns around the entire building perimeters. The safety issues were not caused by special or unique conditions imposed on the structure. Consideration and execution of fundamental issues related to exterior veneer material selection and the installation of a stone veneer system would have prevented all of the unsafe conditions.

Introduction

Two public buildings located in San Antonio, Texas, were experiencing failure of the stone veneer system. For the purposes of this discussion, "failure" is defined as a loss of function or serviceability, including conditions which render a building unsafe. Generally speaking, the failure observed was in the form of stone veneer (both pieces of stone and also entire stones) which had fallen from the façades or were in danger of falling. The buildings were of similar construction with the same types of veneer systems and materials. The buildings were so similar that the topics discussed apply to both; however, where discussed separately they will be referred to as Building A and Building B.

The authors performed an investigation of the cause of failure of the veneer. The structures were approximately six years old at the time of investigation (they were built in the late 1990's); however, stone veneer failure had been ongoing for some time prior. Both Buildings A and B are five-story buildings with conventional reinforced concrete framing. Refer to Figures 1 and 2 for representative views of each building exterior.

The total height of the dimension stone veneer varies from three stories to five stories at each building; with porcelain tile at the remaining portions of the building façades at the fourth and fifth floors. The lighter veneer in Figures 1 and 2 is indicative of the limestone, and the darker-colored veneer is indicative of the sandstone (also, the porcelain tile is visible and is darker in appearance than the sandstone).

Figure 1. General view of Building A exterior.

Figure 2. General view of Building B exterior.

Documents made available during the investigation include architectural and structural plans, the project manual (specifications), and some submittals for the stone, which included pre-construction test data.

Dimension Stone Veneer

General. Dimension Stone is defined as, "a natural building stone that has been cut and finished to specifications" (MIA, 1999). Two main types of dimension stone veneer were used in the veneer for the buildings, limestone with a natural rock face and red sandstone with a natural rock face. All of the stone veneer on the buildings has been observed to have the rift or grain in a vertical orientation. Therefore, the forces from the stones' self-weight are in-line with the direction of the layering within the stone (refer to Figure 3). The specifications indicate a dimensional stone depth of 2 1/2"-3" for the veneer system; and Type N mortar with Type S lime for the mortar in the dimension stone veneer system. A typical dimension stone in the veneer system measures 24" wide x 20" high and has an estimated weight of 115 lbs. The specifications indicate stainless steel anchors, spaced at 18" on-center, for the stone veneer anchors. The design documents indicate a steel lintel support for the veneer at each floor level.

Figure 3. View of stone veneer – note vertical orientation of the grain.

Exterior stone systems must be designed to withstand stresses affecting the building such as: self-weight of the stone veneer, pressure from wind loading, structural movements, thermal expansion and contraction, moisture migration and condensation, wet/dry cycles, and freeze/thaw cycles. To ensure that stone veneer systems are properly designed, material characteristics of the stone must be tested prior to the stones' application on a building.

The primary concerns with the veneer system included flaking of the stone veneer (delamination from the stone surface) falling off the building onto the ground below, some areas of large separations at mortar joints (reportedly increasing in size despite some efforts at previous repair), and progressive movement and deflection of stone veneer above openings. There were no reports of the sandstone delaminating at the structures and only limited amounts of delaminated sandstone were observed at the site in comparison with the limestone. The areas around the buildings are public spaces, some of which are gathering spaces and walkway areas which experience relatively high traffic volume. The delamination of the limestone was of sufficient size and frequency to be a potential danger to the public health, safety, and welfare.

Laboratory Testing. Laboratory testing for the dimension stone (limestone and sandstone) was performed prior to construction, and some additional testing was performed during the investigation.

The project specifications indicate that both the limestone and sandstone are to be Classification II type stone. Considering limestone, the minimum compressive strength is indicated as 12,000 psi and the maximum absorption rate is listed as 5% in the specifications, although ASTM C 568 *Standard Specification for Limestone Dimension Stone* specifies a minimum compression strength of 4,000 psi and a maximum absorption rate of 7.5% for Classification II stone.

The specifications for the sandstone were unclear due to conflicting stone types indicated in the drawings and specifications. Due to the limited occurrence of sandstone delamination, the testing performed during the investigation was focused primarily on the limestone material.

Some of the pre-construction test data was available for review during the investigation of the stone failure. Pre-construction testing of the limestone indicated absorption rates of up to 6.3% and compressive strengths as low as 8,480 psi for the limestone. These test results indicate that the limestone does not meet the project specifications for compressive strength and absorption rate; however, the values from the testing do comply with the requirements of Classification II stone from ASTM C 568.

Pre-construction testing for the sandstone indicated that the compressive strengths and absorption rates of the sandstone material complied with the requirements of a Classification II stone from ASTM C 616 *Standard Specification for Quartz-Based Dimension Stone*.

As part of the investigation of the failed stone, samples of the sandstone and limestone were taken from the site and submitted to a testing laboratory for additional evaluation and testing. Samples of both limestone and sandstone were examined petrographically.

During petrographic examination, the sandstone was determined to be of good quality. This testing also indicated that the internal layering is not pronounced and there does not appear to be a large percentage of impurities present in the sandstone. Based on this evaluation and the general lack of sandstone distress, further testing was not performed on the sandstone.

The petrographic examination of the limestone indicated organic matter, carbon, iron-containing minerals, and clay minerals distributed in the bedding planes. It was also determined that large iron-ore inclusions discovered in the stone could have a negative impact on the durability of the limestone.

The limestone samples were tested for compressive strength and for absorption rate. The compressive testing was performed in accordance with C170 *Standard Test Method for Compressive Strength of Dimension Stone.* The results of the testing indicated that the limestone complied with the requirements of a Classification II stone per ASTM C 568 for both compressive strength and for absorption rate, although some of the compressive strength results were below the 12,000 psi limit of the project specifications. ASTM C 568 also states that, "*Limestone shall be sound, durable, and free of spalls, cracks, open seams, pits, or other defects that are likely to impair its structural integrity in its intended use*." The limestone observed at the buildings does not comply with this requirement, as several stones were observed to have separations and spalls at the bedding planes (Figures 3-6).

Delamination of Stone. Pieces of delaminated stone were noted all along the perimeter of the building (Figures 4 and 5). The stone debris at the surrounding ground was of various sizes, although it should be noted that the size of debris is misleading, as the stone shatters when it falls from the wall above and impacts the ground. The largest debris pieces observed were up to 7" in length (Figure 5) and were generally about 1/4" thick. All of the limestone veneer on the buildings has been observed to have the rift (or grain) in a vertical orientation.

Figure 4. Pieces of delaminated limestone veneer on the ground.

Figure 5. Piece of delaminated limestone measures 7" in length.

As noted above, the dimension stone veneer was specified to be 2 1/2" – 3" in thickness. Stone thicknesses outside of this range were observed at the subject buildings, with stones as thin as 2".

Active delamination was observed at the limestone veneer for the buildings. Figure 6 indicates a piece of limestone which has delaminated from the surface of a veneer stone, but has not yet fallen. This condition exists throughout the exterior veneer walls of both buildings.

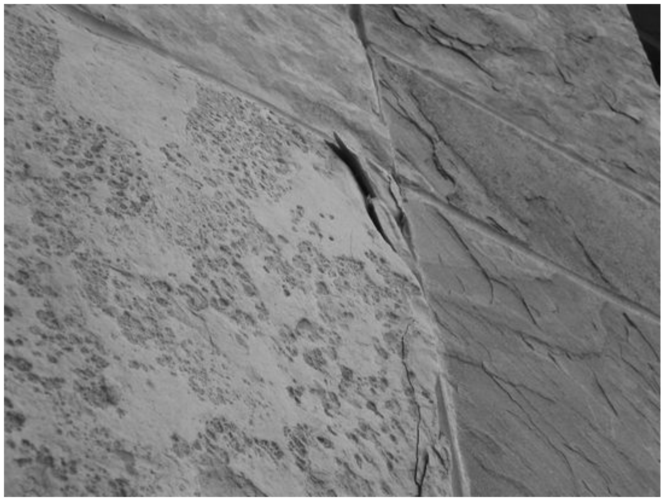

Figure 6. Delaminated limestone veneer at Building A.

The delamination and distress at the sandstone was not as significant as at the limestone. Generally, the sandstone was performing adequately; however, other issues, such as a reduced bearing area due to the lack of a full mortar bed could contribute to future distress of the stone. It is our opinion that the full depth of the mortar joints is paramount to preserving the integrity of both the limestone and the sandstone. The mortar bedding is addressed below in the "Mortar" section.

Expansion Joints. Another issue regarding the dimension stone veneer was expansion joint width. Horizontal expansion joints are indicated on the plans in the exterior walls at each floor level. The expansion joints occur where steel relief angles support the load of the veneer from floor-to-floor (approximately 16'). The horizontal expansion joints occur under the veneer course that rests directly on the relief angle and serve to separate the two fields of stone veneer and transfer the veneer weight to the concrete structure of the building.

The second floor expansion joint is indicated in the design documents for both structures to be 7/8" in width and the expansion joints at the third and fourth floors are indicated to be 3/4" wide. However, a subsequent revision note to the drawings indicates that horizontal expansion joints at all levels are to be 1/2" wide.

During evaluation of the buildings, the horizontal expansion joints were measured to have joint widths typically less than that indicated on the plans. Some expansion joints were completely closed, that is, the stones on either side of the joint were in direct contact (Figure 7). Also, expansion joint sealant material appeared compressed and was observed to be bulging at many joints. Delamination of the stones was observed at the corners of the joints where the stones were in contact.

Figure 7. Delaminated stone pieces with no expansion joint.

Some expansion joints were probed to determine if the joint extends the full depth of the stone veneer. Locations were observed where a knife probe could penetrate only 1/8" inward from the outer surface of the expansion joint sealant. Based on the observed conditions at other joints, it was likely that the stones were in contact behind the sealant, compressing the sealant out of the expansion joint and transmitting expansion stresses between the stone surfaces along the length of the joint. Alternatively, the expansion joints may be filled with mortar behind the sealant.

Measurements of the expansion joints were commonly only 1/4" wide, and several joints were determined to not extend for the full depth of the stone. Also, at some expansion joints, stones were observed to be "buckling" (i.e. deflecting outward at the joint). The lack of proper expansion joints was contributing to the delamination of the stones at the corners. The lack of joints also causes increased stresses in the stone veneer when it experiences movement or expansion, such as related to temperature or moisture.

Mortar. Mortar comprises only a small portion of a stone veneer wall; however, the influence of the mortar on the performance of the veneer wall is disproportionately large. Therefore, degradation or improper installation of the mortar can significantly impact the performance of a veneer wall. Masonry mortar is generally composed of cement, lime, sand, and water. Type I cement is the most common type used. Lime aids the workability and bonding characteristics of mortar and the only lime suitable for masonry work is Type S lime. The mortar specified for the site was Type N mortar with Type S lime.

Considering masonry construction, the most important property of a masonry mortar is bond strength. Workmanship is an important factor in establishing the bond between the mortar and adjacent stones, and full mortar joints must be provided at all contact surfaces for proper bonding (Beall, 1993).

Various instances of loose, displaced mortar were noted along the east side of the veneer clad beams and columns. Mortar was observed missing at joints between the coping stones as well. Generally, the observed mortar bed depth was not in compliance with the depth required by the construction documents. Mortar joint separations measured up to 0.06" in width, and several locations were observed where the mortar had fallen completely out of the joint. At some locations, the pattern of the mortar displacement was indicative of differential movement between the coping stones (pre-cast stone) and veneer stone.

Some samples of the loose mortar were collected and were typically observed to be only of partial depth of the full joint. Close observation of mortar samples indicated a typical intimacy of contact of 80%-90%; however, the intimacy of contact was as low as 60% at some locations.

The most significant sections of missing mortar were observed at the corners of columns, however, large sections without mortar were observed at window openings and building corners also. Based on our observations, the primary causes of mortar displacement are the physical movement of the veneer stones in conjunction with insufficient mortar depth at the joints.

The Project Specifications for both buildings stated that, the stone veneer should be set, *"… in full bed of mortar with vertical joints slushed full, unless otherwise indicated."*

Based on measurements from mortar samples taken from the site, the bed depth of the samples ranged from 1" to 3", and averaged 2" on one building and 1 5/8" on the other. Of the samples from both buildings, 64% had measured mortar depths of 2" or less. Figure 8 indicates a typical piece of mortar extracted from the joints, measuring only 1" in depth.

The lack of full mortar joint depth indicates improper construction and contributes to a loss of strength in the overall veneer wall system. Incomplete horizontal mortar beds would also cause increased bearing stresses at the ends of the stone veneer. This could cause stress concentrations at the stone surface and could contribute to the failure of the stone along lamination planes.

Figure 8. Depth only 1" at extracted mortar.

Veneer Anchorage and Support

Separations and evidence of movement and rotation were observed at the coping stones and windowsill stones throughout both buildings. The material for the coping stones and windowsills was precast stone. Some coping stones could be easily displaced by prying with a screwdriver in the separated joint.

The pattern and type of separations at some of the stone veneer were such that even a brief, non-intrusive evaluation raised concern over safety, especially at high-traffic areas. Further investigation was performed by removing stones or by observation with a scope at selected areas. Some of these are discussed below:

- Building maintenance personnel reported that there had been previous repairs to windowsill stones due to excessive movement. One area had reportedly moved 3"-4" outward from the building necessitating repair. No anchors were discovered during this repair and some remedial anchor clips were provided afterward. At other windowsill stones removed previously, the dowel pins called for in the architectural details were not observed during the repairs and no under-sill anchorage existed. Also, at some windowsill stones, evidence of further movement at repaired stones indicated that the remedial anchor clips were not performing adequately to anchor the stone.

- At the façade of one building, there was a veneer-clad wing wall above a fourth floor terrace area. This wall was topped with coping stones, with the top of the wall angled downward toward the exterior. There was a concrete beam running along the top of the wall (below the coping and veneer). A coping stone was removed from this wall to observe the anchorage of the coping and the condition at the wall cavity. The coping stone was easily removed and was determined to have no anchorage to the structure. Some of the other coping stones were scanned with a metal detector to locate veneer anchors into the concrete beam and veneer; no fasteners were detected.

- At the corner of the fourth floor terrace (at the front façade and located over a high-traffic courtyard area), stone coping and angled veneer were present along the wall. The coping at this corner was observed up close from the terrace above and also with the use of an articulating boom man-lift. Separations and displaced mortar were noted at the joints between the angled veneer stones and between the coping stones. The veneer is angled 45° at this location (see Figure 9 to view the angled stone veneer).

  At the first stone from the corner, mortar was missing from most of the vertical joint and the second coping stone from the corner had apparently rotated outward. Evidence of residual moisture was observed at the joints between the coping and the angled veneer and also at the joints along the bottom of the angled veneer. These joints and the stone adjacent to the joints appeared to be saturated with water.

  A detail in the architectural plans illustrates a section through the sloped veneer and the coping. Per this detail, the angled stone is anchored to a metal stud wall at the bottom by a stainless steel anchor and is anchored into the coping stone at the top by a stainless steel anchor pin. In turn, the coping stone is indicated to be set flush against the concrete frame and anchored with a stainless steel anchor fastening the stone to the concrete. Also, the coping stones are indicated to be supported vertically at the concrete wall by a relief angle. There is no indicated anchorage to the relief angle to prevent lateral displacement. This detail occurred at other areas on both buildings, raising concerns around the building perimeters. Some mortar displacement was noted at the angled veneer at other areas, indicating possible movement.

  At the northeast corner, the stone at the corner was separated 1/4" and the horizontal mortar joint below had fractured, apparently from differential movement. This corner stone and the two stones adjacent were loose. They could be rotated slightly at the outside edge by hand. These stones, especially the corner stone, exhibited a range of rotational movement which was not consistent with the attachment detail indicated in the drawings for the building.

  A metal detector was used to locate the anchors for the coping stones and for the angled veneer. Generally, it was observed that there were two anchors along both the top and bottom of the angled veneer. However, at the corner coping stone, no anchor attachment was noted.

  Because the loose and rotating coping stones at the northeast corner were a concern, a block of the stone veneer at the east side of the corner was removed to allow visibility into the wall cavity and behind the coping. This removed 15" x 7" block was not anchored to the wall at the top or bottom and was only supported by the mortar joints at the bottom and the sides and by the caulk material in the joint along the top of the stone. From this opening, the condition along the back side of the coping stones was visible. Metal shelf angles for the stone railing and for the coping at the edge were noted. Corrosion was observed at visible sections of the angles. Also, the coping was not set flush with the concrete frame and there was no anchor attachment visible from the coping into the concrete. The lack of a coping-to-concrete anchor was noted along the entire visible length at the back side of the coping.

The conditions at this area of the building represented a danger to public health, safety, and welfare.

Figure 9. Angled stone veneer at fourth floor. There is no mechanical horizontal anchorage to the concrete structure.

- The front fourth floor terrace of one structure had a stone balustrade, which separated from a storefront window system for a conference room. Large separations were observed at the vertical mortar joints in the wall below. A vertical column of three spacer stones bridged the gap between the balustrade and the storefront framing. Mortar was missing at the base of the stone assembly, indicating a lack of bearing support. The stones were easily moved and rotated by hand. Further investigation was performed from the building exterior, using the lift. It was noted that the stones were set on a relief angle below the balustrade. The stones were observed to bear on crumbling mortar, a significant amount of which was missing from the outside edge of the support. The gap between the stone and the relief angle was measured as 1/2" at the outer edge.

  Due to the obvious safety concern, the loose stones were removed immediately and were set onto the fourth floor balcony. As these stones were removed, the mortar application at the stone joints was determined to be inconsistent (i.e., uneven and incomplete "buttering" of the stones at the joints). Also, there was no anchorage from the spacer stones to the adjacent baluster stones.

A mortar sample was taken from the joints around the stones after they were removed. The mortar at this location was determined to be Type O mortar and was moderately soft, eroded severely with a high water-to-cement ratio, and of poorer quality than other mortar samples taken from the veneer walls. The quality of the mortar varied greatly even with in the relatively small sample.

- The veneer support was observable at a typical door header condition by using a boroscope to view the wall cavity. A steel angle lintel was observed behind the header stone. Observations in the cavity indicated that the angle was not set into the notch at the back side of the stone. Rather, a metal extension was apparently welded onto the edge of the angle and supported the stone at a notch in the back side of the header stone. This indicates a lack of coordination and/or workmanship during the installation of the veneer system.

- At the main ground level entry to one of the structures, separated and displaced dimension stone veneer was observed. The mortar joints in the stone veneer above the center opening were separated, and a downward movement of the veneer was observed in the approximate shape of an arch starting from the header course above the opening. Figure 10 below shows the displacement of the veneer above the entry and the loose mortar. The separations were measured, as 15/16" at horizontal joints and the mortar was loose and easily removed by hand. Some repairs had been done previously; however, the separations re-opened and the stone continued to displace. Although the support could not be seen from the wall cavity due to excessive mortar, similar details at other openings had a lack of full support for the stone. At one location above another entry door, a gap between the stone and the steel support lintel was observed.

Figure 10. Veneer displacement and loose mortar above entry.

Conclusions

The damage observed at the veneer systems for the subject buildings is related to both design issues and construction issues. The contributing factors to the stone delamination included the selection of the limestone material to be edge-set in the veneer system, the lack of full-depth mortar, and the lack of proper expansion joints.

In addition to the delamination of the dimension stone, differential movement and displacement was observed at veneer which was not properly supported or anchored. The anchors specified at the coping and windowsill stones were not installed during the original construction of the buildings. Also, the dimension stone was visibly displaced at several openings due to a lack of proper vertical support.

Differential movements in the dimension stone due to improper or non-existent anchorage and the lack of proper mortar depth has also caused mortar to be completely displaced from a significant number of mortar joints. Proper anchorage of the stones and proper installation of full depth mortar would have prevented this problem.

The conditions at the dimension stone and coping at the veneer system created conditions which were potential dangers to the public health, safety, and welfare. This case study illustrates how design decisions and execution of support for heavy stone veneers can affect the safety of a building. Consideration and execution of fundamental issues related to exterior veneer material selection and the installation of a stone veneer system would have prevented all of the unsafe conditions.

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