A Case Study of Granite Cladding Distress

Deepak Ahuja, P.E., M.ASCE[1] and Matthew D. Oestrike, P.E., M.ASCE[2]

Abstract

Distress of building cladding is either a symptom of an underlying problem within the support structure or is a sign that the cladding is deficient in some way. Cladding distress typically affects the appearance of the building, may allow unwanted intrusion from the elements to affect and degrade interior materials, and/or may allow the potential for unsafe conditions to develop if conditions are left uncorrected. Like other building components that fail, cladding distress develops from a number of factors that often involves more than just a single cause. The reason why cladding fails and the extent of this failure is a continued topic of debate among engineers, architects, contractors, owners of buildings, and our courts.

Presented herein is a case of exterior cladding distress at a building that includes a search for reasons why the distress occurred based on forensic engineering methods and evaluation. This search concluded that the likely causes of distress for the subject structure were related to corrosion of embedded steel bars, differential movement due to dissimilar materials, excess water infiltration in conjunction with inadequate drainage at the exterior walls, changes in the as-built construction not represented on the plans, and inadequate design coordination/supervision prior to and during construction.

Introduction

The case involves a temple structure located in Texas that was built in 1994-1995. The majority of the temple consists of one and two-story cast-in-place columns and floors (or similar) with granite cladding covering its exterior wall, fascia, and soffit areas. At the back of and connected to the main portion of the temple structure is a shrine that is similarly constructed with cast-in-place concrete and granite cladding with decorative accents. Built above the roof of the shrine and at the back portion of

---

[1] Vice President, Nelson Architectural Engineers, Inc., 2740 Dallas Parkway, Suite 220, Plano, Texas 75093, 469-429-9000.

[2] Branch Manager, Nelson Architectural Engineers, Inc., 13231 Champion Forest Drive, Suite 112, Houston, Texas 77069, 281-453-8765.

the temple rests a dome-like structure. This dome structure consists of a reinforced gunite shell with exterior granite cladding. This dome structure and its exterior cladding distress is the focus of this paper.

The paper will discuss background information related to the structure's construction, details of the structure, and the steps that were undertaken to evaluate the structure and arrive at the most probable causes of cladding distress. These steps included considering and/or ruling out typical causes, making site/structure observations, comparing as-built construction to the plans, evaluating the effects of water within the cavity, evaluating the effects of corrosion, evaluating differential movement of dissimilar materials, field and material testing of the as-built construction, and arriving at conclusions based on the information available.

Background

For discussion purposes, this dome structure is considered a part of the temple, but will be indicated as "dome" within the context of this paper. The dome portion of the temple was designed by an architect based in India and a structural engineer based in Texas. The contractors were based in Texas, and the fabricator of the granite was based in Italy. The dome was built in stages with separate contractors for the shell of the dome structure, the granite cladding, and for decorative accents at localized areas of the dome. No architect or other design professional was involved during the construction of the separate stages of the dome construction. Figure 1 shows an elevation view of the dome, shrine, and remaining temple structure.

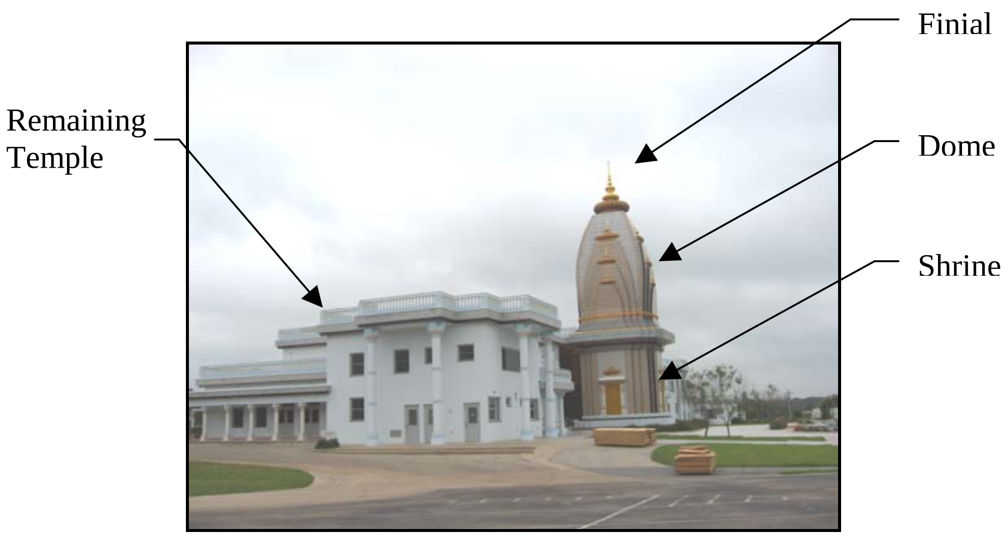


Figure 1. General elevation view.

The owners began to see separations at granite cladding joints and cracks at the granite pieces several years after the dome structure was completed. Most of the damage was located at the dome whereas the remaining areas of the temple sustained only minor damage.

Details of the Structure

The dome was constructed as a gunite reinforced concrete shell structure that extended approximately 43 feet above the top of the shrine and roof of the temple. Thus, the dome is more than 70 feet above the finished floor of the temple. The dome is a curved structure having two intermediate ring beams between the base and the top. The top of the dome is flat with an opening in the middle. The drawings indicate the dome to have a 1'–5" wall thickness at the base of the dome (above the shrine roof); it tapers to a wider thickness between the base and the first ring beam, and then tapers down in thickness at the first ring beam elevation. The wall thickness between the first ring beam and the top is indicated as 8". The dome walls are supported on a thickened structural two-way slab that makes up its floor. Four main cast-in-place columns that bear on straight-shafted piers support the floor slab. Three step-like projections, or "leaves," that follow the curved shape of the dome are located above the temple roof level on each of the four (4) faces of the dome and were constructed monolithically with the dome walls. An elastomeric coating was specified to cover the entire exterior of the gunite dome. After the curved gunite dome was completed, projections at the base of the dome were constructed out of brick and CMU block (neither of which were indicated on the drawings). Figures 2 and 3 show the exterior and the interior of the dome, respectively.

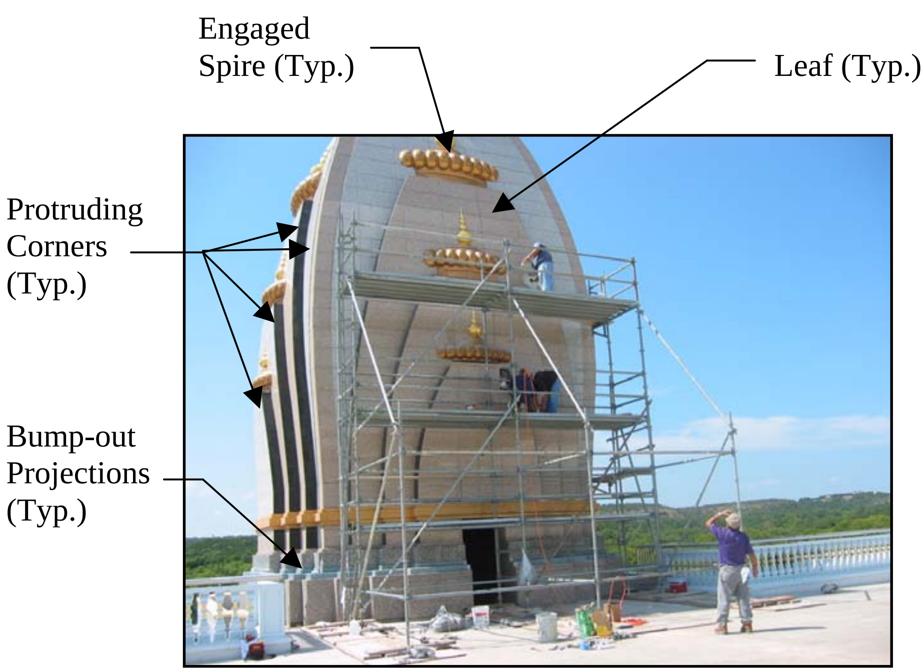
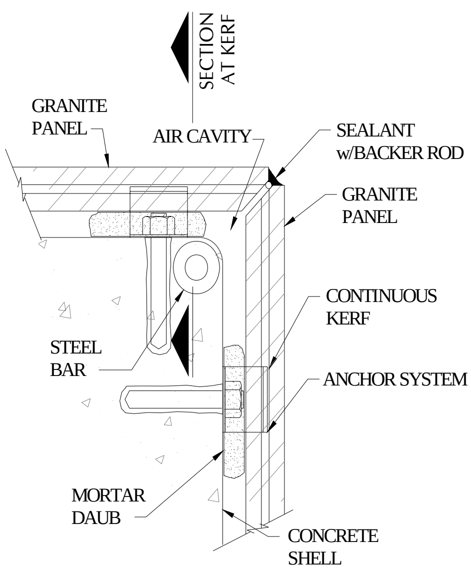


Figure 2. Dome exterior.

Figure 3. Dome interior (looking up).

The cladding on the dome as well as the temple soffits and fascia consists of 1 1/4” thick granite of varying widths and lengths with 1/4” wide by 1” deep continuous kerfs (slots at edges of granite pieces). Stainless steel anchors set (anchored) into the exterior side of the concrete shell of the dome are utilized to independently support the individual granite pieces. Mortar daubs at each anchor location were used during granite installation to facilitate construction of the veneer. The granite joints are comprised of sealant with backer rods used as the joint backing material. Figures 4 and 5 show typical plan and section details of the granite support at the protruding corners of the dome.



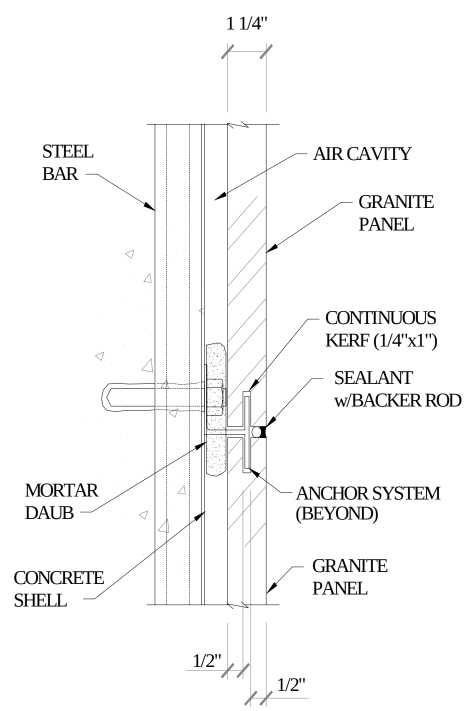


Figure 4. As-built plan at protruding corner. **Figure 5. Section at kerf.**

The sealant joints act as both a moisture barrier for the structure and as control joints for the granite cladding. An air space, indicated on the drawings to be 3/4" to 1 3/4" for the dome and 3/4" for the shrine, separates the exterior face of the concrete shell and the granite veneer. This air space is continuous around the perimeter of the dome except at the top of each of the "leaves," where the air space is interrupted by mortar being utilized to help support the flat granite pieces at these locations. Thus, the exterior wall is intended to behave as a cavity wall system allowing water that penetrates through the exterior veneer or water that condenses within the cavity to drain downward within the cavity space of the wall system. Drainage from the top of each leaf is allowed to occur within the cavity at either of the sides and/or at the front of each leaf. The drainage is intended to continue to the base of the wall where a continuous weep slot (horizontal gap at the base of the cavity running the length of the wall) was specified, so that excess water in the cavity would be allowed to drain. However, this weep slot is covered with a decorative horizontal banded trim that consists of beaded glass stones set in grout around the perimeter of the base (the horizontal banded trim was not indicated on the drawings, Figures 7-9 on next page).

After the granite cladding was installed, a decorative fiberglass "finial" (a crowning ornament or detail, Figure 1) was installed to cap the opening at the top of the dome. Additionally, decorative fiberglass engaged-spires were attached to the granite veneer exterior at the top of the "leaves," located on each face of the dome (Figure 2). A "catwalk" surrounds the base of the dome on three sides and overhangs the shrine that lies directly below the dome. Granite cladding installed at the fascia and soffit bands runs along the face of and below the catwalk.

Typical Causes of Cladding Distress

Cladding problems develop in a number of ways and can be caused by a combination of factors. Some of these include, but are not limited to, the following:

- Differential foundation movement
- Superstructure framing movement (unrelated to effects from the foundation)
- Storm effects from severe wind including windborne debris impact, rain, flood, lightning, hail, ice, etc.
- Movement of the various materials due to temperature, moisture, freeze-thaw, seismic, etc.
- Remedial repairs during construction or after construction completion
- Impact from vehicles, humans, equipment, etc.
- Construction defects of the cladding or components of the supporting structure including inferior or improper materials
- Age and deterioration of the materials
- Volumetric changes in the backup support material due to internal chemical reaction

All of these factors were initially considered prior to visiting the site. Some of these factors were ruled out after initial site observations were conducted as discussed below.

Initial Observations

Dome: An initial visual walk-through of the site confirmed that most of the damage was indeed located at the dome with little distress observed at the remaining portions of the temple. Most of the distress was noted at the protruding corners of the dome. The granite pieces at these corner joints were displaced outward on each side of the joint. Figures 6 and 7 show separations at the protruding corners.

Figure 6. Separation at protruding corner.

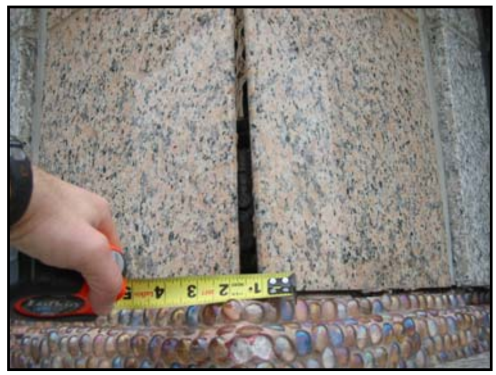


Figure 7. Separation at protruding corner near projection.

Additionally, localized areas of granite developed fractures in the pieces themselves. Evidence of accumulated and excess moisture including staining, efflorescence, and spalled glass beads at the horizontal banded trim at the base of the dome were noted. Figures 8 and 9 show typical areas exhibiting distress.

Figure 8. Moisture staining at base projection.

Figure 9. Granite fracture.

Additionally, moisture staining and efflorescence was noted throughout the interior walls (exposed gunite) of the dome. Hairline cracks were observed primarily at the upper half at the interior of the dome shell. The sealant was weathered with signs of alligatoring, cracking, and holes noted. Furthermore, corrosion was observed at the protruding corners of the dome shell at areas of the granite pieces that were removed prior to our site visit.

Based on the reported information and initial walk-through of the structure, there were no significant signs-of-distress that could be related to movement of the foundation or to differential movement between the dome and foundation. Hairline cracking at the top of the dome appeared to be related to normal shrinkage or not significant enough to cause the noted cladding distress. Additionally, the cladding distress was not noted after any significant storm event that one might correlate to severe wind, hail, lightning, etc. The site is located in a temperate climate zone, where freeze-thaw problems of masonry are not an issue. Additionally, there were no significant remedial repairs, seismic events, impact events that could have caused the noted distress. Furthermore, the cladding distress was on all sides of the dome; however, appeared to be localized to certain areas of the dome shell.

Shrine (located below Dome): The shrine cladding is protected from water intrusion by the presence of the catwalk at the roof elevation. This catwalk protects the top portion of the shrine cladding from any direct rain and any potential water infiltration that may enter the top of the cavity. Additionally, a continuous weep slot at the base of the shrine was observed allowing any water penetration through the cladding to drain out of the cavity. No fractured or displaced granite was noted. Some of the sealant appeared to have weathered/degraded.

Remaining Temple (excluding Dome and Shrine): The remainder of the Temple beyond the Dome and Shrine structure was evaluated for signs of distress. The majority of the granite cladding installed at the soffits and fascia on all terrace/roof levels, Porte-cochere, porch and at perimeter of the Temple building, revealed little to no distress. The granite in almost all of the locations was in good condition. The primary area of distress was at a few of the sealant joints at the protruding corners of the terrace fascia. These separations ranged from hairline to approximately 1/4” in width. Additionally, some weathering of the sealant was observed without any adhesion failure at the interface between the sealant and the granite substrate. Some moisture stains were noted at the base of the granite cladding walls.

As-Built Construction

The as-built construction of the dome revealed differences and/or modifications from the design drawings. The concrete shell appeared to have been constructed in accordance to the structural drawings. However, the structural drawings did not show the as-built bump-out projections that were observed at the base of the dome (Figure 8). Samples taken at these projections, considered along with the noted observations, indicated that the projections were constructed of various materials including CMU block and at least two different types of brick masonry. Additionally, steel hollow sections (bar/tube) were noted at the edges of the protruding corners of the dome shell (Figures 4-5). There was no indication on the structural drawings that steel hollow sections (bar/tube) were to be installed. The horizontal blue and pink beaded stone bands were built after the granite was installed (Figures 7-9). No indication of this type of installation and construction was noted in the shop drawings or in the architectural schematic drawings. Details and/or specifications for the horizontal bands were not prepared. Therefore, the contractor installed the horizontal beaded bands under no design supervision, did not conduct the work based on any specific details provided by a design professional, and was not aware of the necessity of allowing the cavity wall to weep excess water. Furthermore, the structural drawings indicated that the dome shell was squared off and open at the top. Observations indicated that the top of the dome consisted of an additional concrete shell, above the specified opening, that was not indicated on the structural drawings.

Water in Cavity

From observations and testing, it was clear that water was entering into the exterior wall cavity between the granite cladding and the dome shell. Entry points for water to infiltrate into the cavity existed at many of the sealant joints primarily at the protruding vertical corner joints where separations were observed. Additionally, there are openings at the “curb” located at the top of the dome where the top finial was attached. These openings are in the form of gaps, holes, and hairline separations. At the interior of the dome, dripping water was seen coming from the top of the shell. Efflorescence, mineral deposits, and moisture staining were prevalent throughout the exposed concrete dome interior (Figure 3). Additionally, the moisture readings taken at the surface of the shell interior indicated that the shell was wet. All of these factors provide evidence that water is penetrating the dome envelope by either entering through the cavity and/or from around the top finial and then leaching through the shell to the interior of the dome. Furthermore, separations at the horizontal butt joints at the outer edge of the flat surfaces of the dome (top of dome and top of “leaves”) and unsealed screw holes that were drilled through the face of the granite to aid in attaching the engaged-spires to the faces of the dome, are other points of water infiltration.

Evidence of the effects of this water intrusion is noticed at the dome exterior especially at the blue beaded stone bands that surround the base of the dome (Figure 8). Additionally, upon removing the granite panels and at locations where the granite had already been removed, bubbling and blistering of the paint/coating that was applied over the CMU block was observed. Additionally, mineral deposits were observed to be leaching through the coating from the bump-out projections/shell locations. The mineral deposits and bubbling/blistering is a typical affect of water transpiring from the shell and/or CMU block through the applied paint/coating. Rust streaks and corrosion of the embedded steel hollow sections were observed at the protruding corners of the shell. Corrosion and the effects thereof are discussed in detail in the following section.

Corrosion

A hollow section steel bar was embedded (cast-in-place with the concrete) at the protruded corners of the shell without an effective cover or clearance. It was noted that the cover over the hollow steel bar was either non-existent at corroded portions along the bar or very thin at other locations. Due to the lack of an effective cover, the bar was exposed to the elements in the cladding cavity. This exposure resulted in significant corrosion at the hollow steel sections. No signs of protective coating in the form of galvanization or paint on the hollow steel section was noted on the steel bar. The embedded bar does not perform a load bearing or structural purpose and was not shown on any of the drawings. It is not clear what function the exposed steel bar served other than to aid in forming the shell. If a bar was required for reasons, which were not structural, then it is not clear why a steel hollow section without any protective coating was used.

Water and oxygen are essential for corrosion to occur. The lack of any cover at these protruding corners in conjunction with the abundance of water affecting the exterior of the shell, allowed corrosion to develop and affect these metal bars/tubes. Unhydrated ferric oxide (Fe_2O_3), or rust, when fully dense has a volume of about two times that of the steel it replaces. Broomfield (Broomfield, 2003) reports that when ferric oxide gets hydrated it swells even more and becomes porous. Hydrated ferric oxide ($Fe_2O_3.H_2O + 2H_2O$) is approximately two to ten times the volume of original steel. Kaminetzky (Kaminetzky, 1991), reports that the increase in volume of rusted embedded steel (typically reinforcing bars) produces internal pressures in the concrete that split the concrete in the path of least resistance. Figures 10 and 11 are typical views of the effects of the corrosion at the protruding corners of the shell.

Figure 10. Corrosion at protruding corner of dome shell.

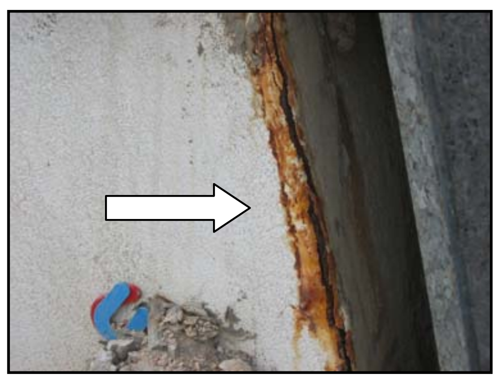


Figure 11. Similar as Figure 10 at another location.

The stainless steel anchors supporting the granite cladding at the sides of the leaves are centered on the individual granite panels. The center of the side panel and attachment of the stainless steel anchor along with the surrounding mortar daub is proximate to the embedded hollow section steel bar in the concrete shell and is not centered on the side face of the shell. The corrosion of the embedded steel bar has created rust products which have increased the volume of the original steel. This volume change due to the formation of rust has created expansive forces onto and through the mortar daubs and the anchors, which in effect have pushed the granite panel at the side of the leaves outward (away from the shell). This results in opening of the sealant joints at the protruding corners of the cladding. On the other hand, the flat faces of the leaves (front granite panels) have mortar daubs/anchors located away from the protruding corners of the shell and, thus, have not been subjected to any expansive forces from the corroding hollow steel sections. This creates a condition where one side of a cladding corner is moving outward causing a separation, while the other side of the corner joint is relatively stable. This also explains why there is no separation at any of the re-entrant corners. It was observed that the corroded hollow section steel bar has moved in the order of 1/4" from its original position.

Furthermore, fractures at some of the granite panels (black in color) located at the sides of the leaves, correlates with the area of the stainless steel anchor attachment. As discussed above, the stainless steel anchors were attached to the shell, proximate to the corroding steel bar. The expansion creating by the corroded bar led to outward pressure at the anchor. This resulted in the split-tail portion of the anchor, which was attached to the granite panel, to induce an outward force on the sides of the kerf located at the center of the granite panel. Figures 12 and 13 show how the corroded bar affected the granite.

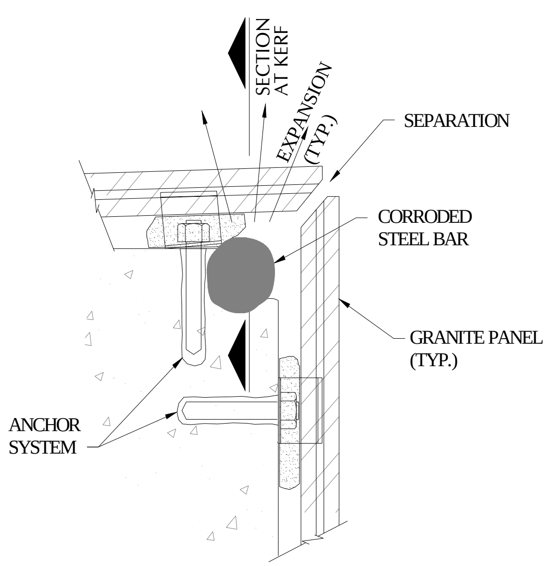


Figure 12. Plan at protruding corner after corroded bar expansion.

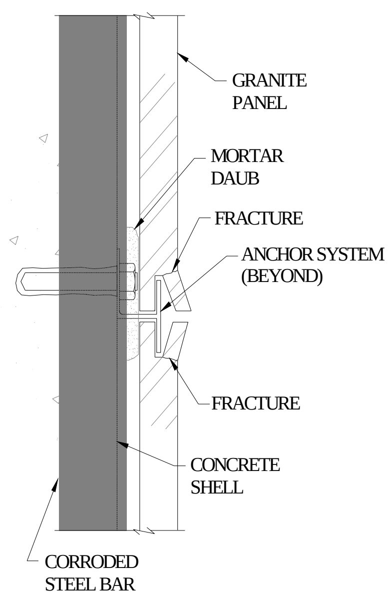


Figure 13. Section at kerf after corroded bar expansion.

The panel is 1 1/4” thick with a 1/4” wide kerf. The granite thickness on each side of the kerf is approximately 1/2” thick. The section at the exterior face of the kerf is less than half the thickness of the panel (approximately 1/2”) and is weakest at this location. The outward movement of the anchor creates a localized bending and shear at the exterior face of the granite panel. Where the capacity of the granite panel has been exceeded, it is exhibiting fractures.

The corrosion of the embedded steel hollow section is proximate to the observed distress. Most of the distress at the dome is in the form of separations at the protruding corners and at the granite pieces at the sides of the leaves where the stainless steel anchors are attached to the kerfs. The expansive effects created by the corrosion of the embedded steel at the protruding corners, explain the type of cladding distress observed.

Differential Movement due to Dissimilar Materials

As reported by Beall (Beall, 1993), bricks (clay) expand from exposure to moisture and to variations in temperature. Conversely, concrete shrinks as it cures. At the base of the dome projections, which exist above the roof of the temple, brick and CMU block were used. The projection at the base of the dome consists of CMU block forming the outer most projection, with brick masonry above the CMU to form the next step of the dome projection. Brick masonry is adhered to CMU without a bond breaker. The expansion of the masonry and the opposing CMU shrinkage has caused separations in the joints at the protruding corners of the dome projections (Figure 7). The reason the separations happen at the protruding corners and not the re-entrant corners is that the protruding corners have the least restraint to movement. This explains the separations at the southwest corner of the dome where the dome projects outward. At this location, the embedded steel bar/tube is not present and the brick is supported on CMU.

Field Testing

Field-testing of the sealant at the granite joints was conducted to see if there were any deficiencies in the adhesion of the sealant that may have led to the noted separations at the granite joints. The in-situ field adhesion tests were conducted in substantial accordance with “Method A of Field-Applied Sealant Joint Hand Pull Tab” (ASTM C 1193-00, 2000). The tests on the dome sealant concluded that both types of sealant utilized were not defective and that, in general, the adhesion was acceptable. However, the alligatoring and cracking of the sealant indicated that there were signs of weathering from normal age and exposure.

Elevated surface moisture readings and humidity readings within the dome verified the moisture staining, efflorescence, and mineral deposits observed at the surface of the gunite/shotcrete dome interior. Moisture readings were as high as 100% (relative) at many of the locations.

Material Testing

Material testing was conducted to further evaluate the conditions at the structure. Additionally, materials testing was used to confirm whether or not specifications were met and/or if deficiencies in the materials exist that may have led to the observed cladding distress. Since the majority of the granite appeared to be in relatively good condition (except at localized areas), it was important to verify the characteristics of the material that was either attached to or in back of the granite. Additionally, material testing was used to verify conclusions reached by others from prior material testing results. Prior chemical analysis and petrographic examination testing of the mortar daubs by others concluded that the primary cause of the cladding distress was related to the expansion of the mortar due to sulfate attack (expansive reaction that can cause cracking in the mortar).

Additional field sampling and testing of the brick, mortar, and gunite (concrete) shell materials at the dome was conducted in order to perform chemical analysis and petrographic examination on the material samples. Additionally, sampling was also conducted at the terraces of the Temple building. Sampling locations were chosen in order to verify laboratory results of samples that were previously taken by others as well as to evaluate laboratory data of the material at other representative locations.

Twenty samples taken from the site were sent to an independent qualified laboratory (CTL[3]) so that chemical and petrographic testing could be performed. The purpose of the laboratory testing was to verify the amount of sulfur/sulfates and ettringite that were present within the material through chemical analysis and to provide other information related to the material (as required) through petrographic examination.

Laboratory Testing: Chemical analysis included X-Ray Diffraction (XRD), X-Ray Fluorescence Spectrometry (XRF), and LECO Total Sulfur testing on the samples. The hardened mortar and concrete samples were analyzed by XRF for 14 chemical elements and multi-step loss on ignition. Additionally, 3 samples were analyzed for total sulfur and expressed as SO_3 by LECO Total Sulfur testing. Chemical analysis results of the samples are summarized below.

<u>Chemical Analysis Results from XRD Analysis:</u> The XRD analysis of Mortar – Samples #2, #3, #4 and #8 indicated the presence of calcite, aragonite, quartz, gibbsite, calcium aluminate, and brownmillerite. Gypsum was also found in Mortar – Sample #5, #6, and #7. The coating on the glass beads shown on Core Sample #9 was predominantly calcite. Secondary ettringite was not detected.

<u>Chemical Analysis Results from XRF Analysis and LECO Total Sulfur Testing:</u> The sulfur content was determined by XRF and by LECO Total Sulfur (as noted) for each

[3] Construction Technology Laboratories, Inc. (CTL) performed chemical analysis and petrographic examination of the samples and prepared an unpublished report (dated November 2, 2004) of their laboratory results.

of the samples and in the unused mortar. The chemical analysis by XRF resulted in SO_3 contents between 0.45 – 1.67 (weight %). The LECO total sulfur analysis of mortar samples yielded results between 0.82 – 2.0 (weight %). Previous testing by others indicated an average of 2.26% SO_3 (by mass of sample) by LECO total sulfur analysis. This is compared to CTL's results that determined that the mortar at the dome had a total sulfur content of 0.82% and 2.0% SO_3 (by weight %) respectively, by LECO total sulfur analysis. The differing sulfate amounts are explained by CTL as being due to the ettringite (normal under hydration process) converting into gypsum, gibbsite and calcite/aragonite in the presence of carbon dioxide, moisture and facilitated by high temperature. The cracks in the mortar were due to shrinkage, which occurs with such a chemical reaction. This finding was contrary to assertions made by the previous laboratory.

Petrographic analysis on the mortar, grout, and gunite (concrete) was conducted in accordance with "Standard Practice for Petrographic Examination of Hardened Concrete" (ASTM C 856-04, 2004). ASTM C 856 is often used for petrographic examination of mortar and/or cementitious grout as well as concrete. The purpose of the petrographic examination was to gain insight into the composition, curing history, condition, and usage of the mortar/grout/concrete by viewing the samples under a microscope. Petrographic examinations of hardened concrete/mortar can be used to estimate cement content/type, water-cementitious material ratio, the aggregate content and grading, color, microcracking, depth of carbonation, nature of the air void system, secondary deposits, etc. These methods can assist in determination of the quality of the mortar/grout/concrete when originally cast, causes of distress, and the degree to which damage has occurred within the material.

<u>Petrographic Results of Mortar:</u> In general, CTL found that the cementitious matrix of the mortar primarily consisted of calcium-aluminate cement and lesser amounts of Portland cement and calcium sulfate compounds (originally either gypsum and/or plaster). The mortar samples have undergone one or more alteration stages that appear to have contributed to non-uniform degradation of paste properties and localized cracking/microcracking. Carbonation of the cementitious matrix was found to be extensive in most of the examined sample fragments and appears to have contributed to changes in the mineral composition of the mortar including the formation of secondary compounds and deposits. Carbonation is a "normal reaction in most Portland cement-based construction materials, with the degree and rate of carbonation mainly dependent on the relative permeability of the cementitious matrix." The secondary compounds and deposits consisted of calcium carbonate, gypsum, ettringite, and other crystalline compounds.

<u>Petrographic Results of Gunite (Concrete):</u> The gunite (concrete) samples were in generally good condition. Traces of alkali-silica reaction gel were found in at least one core; however, no significant cracking was found around the sparsely affected aggregates and no evidence of significant distress was found in the concrete. Outer surfaces of the samples revealed remnants of finish mortar and textured, elastomeric paint. Many of the cores exhibited secondary deposits of primarily calcium carbonate

at the outer edge of the elastomeric paint and/or beneath the paint. Some secondary deposits of ettringite were observed in voids throughout most of the examined core samples. The cementitious binder of the samples is extensively hydrated, and considered along with the presence of secondary deposits (as described above), suggests that the wall was at least periodically kept in a moist to saturated condition while in service and that some of this moisture has migrated through the gunite (concrete).

CTL concluded that the subject mortar was not expansive and might have undergone a reversal of the hydration reaction explaining the difference in the sulfate amounts. CTL concluded that cracks of the sampled mortar were due to leaching, heating and cooling, and wetting and drying of the mortar. Additionally, CTL concluded that the subject mortar was not expansive by mixing the subject mortar with water and then setting it in a glass jar while it hardened. They also did the same for a known expansive mortar. The results revealed that the expansive mortar fractures the glass jar as it expands whereas the subject mortar does not.

Conclusions

Based on the information available, documents reviewed, analysis, site observations, and testing conducted; we found that the **primary causes** of distress are related to the following:

- Volume change due to corrosion of the embedded steel bar/tube at the protruding corners of the dome shell.
- Differential movement due to dissimilar materials at the base of the dome.
- Excessive amount of water infiltration into the wall cavity of the dome without a proper means to drain the excess water. Entry points for water were noted at the sealant joints between granite panels primarily at the protruding corners, at the curb where the top finial was attached, improper horizontal (butt) joint at top of dome, and unsealed screw holes for the engaged fiberglass spire attachments.
- As-built construction was not represented on the plans/drawings.
- No design coordination between the different design disciplines or trades prior to the construction.
- No design professional involved onsite to conduct any construction administration and/or supervision during the building of the dome.

The majority of the cladding distress is proximate to the corrosion observed at the protruding corners of the dome. Other contributing factors that led to isolated granite fractures are related to the presence of mortar in the kerfs in conjunction with chronic water penetration, likely fissures in some of the granite pieces, and isolated areas of improper construction at the face of the leaves. Furthermore, differential foundation movement, wind, wind-borne debris or impact, lightning, hail, or seismic activities were identified as having no contribution to the cladding distress.

References

American Concrete Institute (ACI). (1995). *Building Code Requirements for Structural Concrete (ACI 318-95)*, Detroit, MI, 1995.

American Society for Testing and Materials (ASTM). (2000). ASTM C 1193-00 *Standard Guide for Use of Joint Sealants,* West Conshohocken, PA, 2000.

American Society for Testing and Materials (ASTM). (2004). ASTM C 856-04 *Standard Practice for Petrographic Examination of Hardened Concrete,* West Conshohocken, PA, 2004.

Beall, Christine. (1993). *Masonry Design and Detailing For Architects, Engineers, and Contractors,* Third Edition, McGraw-Hill, Inc.

Broomfield, John P. (2003). *Corrosion of Steel in Concrete*, Spon Press.

Kaminetzky, Dov. (1991). *Design and Construction Failures: Lessons from Forensic Investigations*, McGraw-Hill, Inc.