WASHINGTON MONUMENT
Post-Earthquake Assessment
National Mall, Washington DC

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EXECUTIVE SUMMARY

On August 23, 2011, the Washington Monument was subject to seismic ground motion from the Mineral, Virginia earthquake. The purpose of this assessment is to describe the type and extent damage observed and to develop a preliminary scope of work for the repair of earthquake-related damage to the monument, based on field investigations that have been completed considering access limitations.

Due to the short notice given for the initial site visit (August 25 and 26, 2011), the initial site visit was conducted concurrently with limited review of background documents on the structural design of the monument. Prior to the follow-up site investigation (September 26 to October 5, 2011), documentation provided by the National Park Service was more thoroughly reviewed, including some information pertaining to the original design, the historic structure report, previous condition survey reports, repair documents, and photographs. The follow-up site investigation included a limited visual inspection of the exterior of the monument, via roped access techniques, to develop a sense for current conditions and to serve as a baseline for future evaluations. Conditions observed during the visual inspection were documented with photographs, drawings, sketches, and field notes. Based on information gathered through the investigation, preliminary repair options were developed.

Findings

The observations of earthquake damage, to date, summarized below, provide the basis for the preliminary scope of repairs developed as part of this study.

Pyramidion

- Six marble panels that form the exterior surfaces of the pyramidion developed earthquake-related cracks that extend through the full thickness of the panel. These through thickness cracks also extend over the full height of the panel and vary from approximately 1/4 inch to 1 inch in thickness. Three additional panels developed cracks that do not appear to have migrated through the full thickness of the panel.
- A number of marble panels that form the exterior surfaces of the pyramidion formed spalls at the corners of the marble panel units. The exterior spalls that were small enough to be able to be removed by roped-access techniques and were considered falling hazards were removed during the exterior survey. The spalls that were too large to be removed during the survey were documented but left in place. The spalls that were left in place appeared to be stable in their current locations.
- The portions of the marble rib units that serve as bearing surfaces for the support of the exterior marble panels experienced cracking. Cracking of the rib bearing surfaces occurred on some of the ribs on each of the four sides of the pyramidion.
- A large spall was generated directly below the cruciform shaped keystone of the pyramidion in the ‘H’ rib course of the pyramidion.
- The majority of the tie beams in the ‘F’ course of the pyramidion experienced vertical cracks at their connections to the rib units.
The southwest cornerstone unit at the ‘G’ course experienced a permanent lateral offset to the south of approximately 1 inch, and to the west of 1/2 inch, relative to the stone unit of the rib in the course below.

Components of the lightning protection system have been displaced.

There is a lateral offset up to 3/8-inch at a horizontal joint in at least two of the arch ribs on the east side at the display level.

The vertical joints of the stone panels of the pyramidion have been damaged and are allowing water infiltration into the interior.

Areas below the Pyramidion

- Mortar on the interior and exterior face of the masonry is missing at numerous vertical joints from the 450-foot level to the 500-foot level of the monument. Daylight is visible at a number of the vertical joints where mortar is missing.
- Water leaks from a number of vertical and horizontal joints in the masonry.
- Following rain, a substantial amount of standing water collects on the floors of the display and observation levels, and the stair landings to the 450-foot level.
- The steel rod members which serve the purpose of retaining the elevator counter weights were bent.
- The sheared end of an approximately 5/8-inch diameter bolt was discovered by the NPS maintenance staff.
- Spalling of the exterior stone was observed over the entire height of the shaft of the monument with spalls being larger and more clustered above the 450-foot level. Some spalls at this level were the full thickness of the masonry block.
- Thin shelled mortar patches with encased loose debris on the exterior are prevalent below the 160-foot level.
- Previously repaired cracks on the exterior that are multiple courses in height have failed sealant and new cracks adjacent to the previous cracks or extending from the previous cracks.
- Lateral movement and offsets on the exterior were observed above the 450-foot level, and were pronounced at the southwest corner of the monument.
- Loose and degraded mortar on the exterior was found in most of the joints above the 450-foot level, with similar conditions found less frequently below this level.

Recommendations

Repair recommendations have been developed based on the fieldwork and review of background information. Because of the deleterious effects of water infiltration, some short-term stabilization efforts would be prudent until long-term repairs can be designed and implemented.

- Document water leakage locations during or immediately after a rain storm. This information should assist with the temporary weatherization of the monument.
- Install the temporary weatherization measures.
- Complete a survey of the elevator framing for earthquake damage with recommendations for repair.
- Perform a detailed interior survey to document earthquake damage in the monument.
- Develop long-term repairs for earthquake distress in the monument.
- Perform a preliminary seismic study to evaluate the vulnerability of the monument to earthquake ground motion and develop associated costs for these improvements.
BACKGROUND

At the request of the National Park Service (NPS) Denver Service Center, Wiss, Janney, Elstner Associates, Inc. (WJE) and Tipping Mar conducted a post-earthquake assessment of the Washington Monument, located in the National Mall in Washington DC to address damage related to the Mineral, Virginia earthquake of August 23, 2011. As a result of earthquake-related damage, NPS decided for the safety of visitors to restrict public access to the Washington Monument. WJE and Tipping Mar arrived on site on August 25, 2011 and concurred with the NPS decision to restrict public access to the monument, on the basis of earthquake-related damage that was observable.

The purpose of this assessment was to develop a preliminary scope of work for the repair of earthquake-related damage to the monument. The preliminary scope of work is based on information gathered from our fieldwork, and our limited review of pre-existing damage documented in previous studies, given the time frame available. Additional investigation is necessary to refine the scope of recommended repairs and to confirm details for the development of contract documents for repairs.

Methodology

The scope of the post-earthquake damage assessment of the Washington Monument consisted of three phases.

2. More detailed review of documentation provided by NPS from the original design, previous condition surveys and investigations, previous repair documents, photographs, and the historic structure report.
3. Exterior survey using roped-access (September 26 to October 5, 2011).

As part of the initial post-earthquake damage assessment, and in an effort to assist NPS with immediate stabilization, and to allow the monument to be safely accessed by our own personnel and NPS staff, WJE removed spalls and incipient spalls from the interior of the pyramidion. In advance of Hurricane Irene, WJE installed temporary waterproofing, consisting of backer rod and acrylic sealant, at three cracks in the marble pyramidion panels. WJE also installed backer rod and acrylic sealant at visible and accessible open joints on the interior face of the masonry from the 500-foot level to the 450-foot level. Some locations could not be sealed during this effort because the cracks or joints are not physically accessible, due to the glazing system installed at the 500-foot and 490-foot observation and elevator re-boarding levels.

Prior to beginning the follow-up site investigation, representatives of the project team met with NPS at the site to review the scope of the investigation and logistical considerations for access. Also, office tasks completed prior to the follow-up site investigation included development of field notebooks including survey sheets (baseline drawings) and reference drawings from original construction and subsequent repair campaigns, for reference and data recordation in the field; development of a work plan and safety plan for site work; and coordination with NPS.

Abbreviated Construction History

The following is a brief construction history, for the purposes of providing historic context for the understanding of our assessment and repair recommendations. The primary source for this abbreviated
history is the 2004 Historic Structure Report (HSR) on the Washington Monument and Associated Structures.¹

The Washington National Monument Society was established in 1833 to spearhead the planning and financing of a memorial to George Washington in Washington D.C. The society raised funds and held a competition for the design of the monument in 1836, but a design was not selected from those submitted. In 1845, after additional fund-raising, the society selected a design by Robert Mills. Mills’ monument design consisted of a 600-foot tall obelisk surrounded by a 250-foot diameter, 100-foot tall pantheon, with an estimated cost of $200,000. Construction commenced in 1848, but was halted due to lack of funds in 1854, when the monument was approximately 156-feet in height.

The Washington Monument remained in a partially complete, unfinished state until after the Civil War. Approaching the nation’s centennial, renewed interest in the completion of the monument took shape and ownership was transferred to the federal government in 1876. The Army Corps of Engineers was commissioned to study the integrity of the foundations. Their studies led to structural modifications, which began in 1878 under the direction of Lieutenant Colonel Thomas Lincoln Casey, Chief Engineer of the monument construction project. The foundation-strengthening work was completed in 1880, and construction resumed on the superstructure of the monument that year. Six feet of previous construction was removed and work on the shaft commenced from the 150-foot level. Casey developed an internal iron structure for the monument to support the work platforms and the steam-powered hoist. He redesigned the monument somewhat by adjusting the proportions of the pyramidalion to conform to those of known ancient Egyptian obelisks, a design strategy which also influenced the design of the final height of the structure. The final design of the obelisk consisted of a 500-foot shaft, topped by a steeply sloped pyramidalion 55-foot in height.

The Washington Monument was dedicated in 1885 and opened to the public in October of 1888. Since that time it has become one of the most recognizable and symbolic structures in the nation. Generations of Americans have enjoyed visiting the Washington Monument and repair campaigns have been executed periodically in an effort to maintain it. See the section “Pertinent Repairs” for a brief summary of previous repairs that have the potential to influence repair recommendations.

Description of Monument

The Washington Monument stands 555 feet 5½ inches tall with a base 55 feet 1½ inches wide on each side.² The monument shaft tapers approximately ¼-inch per foot from the base, up to the 500-foot level, which marks the end of the shaft and the beginning of the pyramidion (Figure 1). The monument is 34-feet 5½ inches wide at the 500-foot level. A small inscribed cast-aluminum tip, an extraordinarily rare product of its time, is featured at the top of the 55 feet 5½ inches tall pyramidion. Structurally, the Washington Monument is a stone-masonry bearing wall structure. It is largely a hollow shaft, with archaic iron interior framing that supports the elevator structure and the interior stair structure.

The foundation of the monument is constructed from stone masonry, and is reportedly 80 feet by 80 feet. Significant underpinning of the foundation with concrete was performed by the Army Corps of Engineers prior to commencing the completion of the shaft.

The structural stone masonry of the monument is constructed of a variety of types of stone. The shaft thickness also varies, depending on the height of the structure relative to grade. A description of the various types of construction is given below.

The lowest portion of the monument (from grade to 150 feet) was constructed in 1848-1858. The shaft walls are constructed of gneiss on the interior and Texas marble from Texas, Maryland on the exterior of

² Ibid.
the shaft. The space between the interior and exterior stone is filled with rubble stone masonry, but the extent of voids within the rubble stone is unclear. The shaft wall thickness at the base is 12 feet 2 inches and the shaft tapers to 11 feet 8 inches at the 150-foot level.

The next segment of the shaft (150 feet to 500 feet) is the segment begun under the Army Corps of Engineers. Between 150 feet and 160 feet, there is a steep taper at the interior of the shaft that widens the interior space within the shaft. The interior walls of the shaft are constructed of blue gneiss and granite stone masonry units, transitioning to marble at the 452-foot level. The exterior stone masonry units are two types of marble; four courses of Lee marble from Lee Massachusetts and the balance of the marble is Cockeysville marble from Cockeysville, Maryland. The shaft walls are multiple Wythes of masonry. The stone masonry was mortared with a lime mortar. The shaft wall thickness at the 160-foot level is 8 feet 7 inches and the shaft tapers to 1-foot 6 1/2 inches at the 500-foot level. At elevation 218-feet and above, the stone units that form the header course of the exterior marble, extend the full thickness of the shaft wall and can be observed from the interior of the shaft. At elevation 460-feet and above, the stone masonry shaft wall is a single Wythe of marble. The single Wythe construction includes mortise & tenon joints in the bed courses, and 3/4-inch bent rod iron cramps connecting adjacent stone units in the mortared bed joint, intended to prevent lateral movement.

Monument Terminology

In order to help describe the observed earthquake damage, the following terms are used in this report to describe various elements of the monument:

**Cornerstones** - These are large 2 feet 8 inch square blocks that cap the two side ribs that come together at each corner of the pyramidion at course ‘F.’ There are four cornerstones that are located at the interior corners of course G (525) within the pyramidion structure.

**Courses and Course Numbers** - This describes one horizontal level of stone masonry. Courses within the shaft of the monument are typically 2 feet in height and are therefore numbered accordingly (282,284,286, etc.). The first course at the base of the shaft begins with the number two, not zero. Therefore the course number indicates the height at the top of the numbered course or block. Course numbers are preceded by a single letter denoting the cardinal direction (N,S,E,W) and followed by a unique identifier number that is sequential from left to right on the indicated elevation. For example W.496.6 is the sixth stone from the left corner on the west elevation in the course that reaches the 496-foot level. Courses within the pyramidion exterior follow the same numbering system with courses numbered every 4 or 5 feet. The portions of the interior ribs above the 500-foot level are numbered alphabetically beginning with ‘A’ at the 504-foot course, continuing up through K and skipping the letter J.

**Cruciform** - This is a cross shaped keystone that occurs at course ‘H’ of the pyramidion structure, and is engraved with the year 1884 on the underside.

**Haunch** - This term describes the upper- and outer-most portion of every block that is a part of the pyramidion’s rib structure. This is a tab or a tenon that serves to support the exterior panel of the course above. This is often referred to as a rib projection and has been referred to as a shoulder at times in historic documents.
Knuckle - This is a thickened portion of stone on the lower interior portion of the pyramidion’s exterior panels. It acts as a mortise or notch and rests upon the haunch of the course below. This has been referred to as a bracket at times in historic documents.

Panel - This refers to the exterior panels of pyramidion structure. They have been referred to as roof panels at times in historic documents.

Pyramidion - This is the upper 55 feet of the monument that features larger exterior courses and a more pronounced slope.

Rib - This refers to one of 12 structural elements that serve to support the exterior features of the pyramidion. There are three ribs on each side of the monument with the center rib longer in plan dimension than the two side ribs. The ribs begin at the 470-foot level and are integrated within the shaft structure at every other course. They become free standing above the 500-foot level and support the exterior pyramidion panels.

Tie Beam - This refers to one of eight structural elements that run laterally at course ‘F’ and serve to connect the ribs to one another at the point where the shorter side ribs terminate.

Pyramidion Structure

The pyramidion exterior of the Washington Monument is comprised of twelve courses of large marble panels that appear to be stacked in the same manner as the shaft below. In fact the panels are supported by a system of interior stone arches that spring from the 470-foot level. These 1 foot wide structures, known as ribs, form the bulk of the system that supports the pyramidion. There are 12 ribs in total, three within each face of the monument. The lower halves of the ribs are integrated within the shaft structure by alternating courses of the ribs that penetrate the shaft to the exterior. These penetrating rib stones appear on the exterior of the monument as 2 feet square blocks which align vertically every other course in three vertical bands on each elevation from the 470- to 500-foot level. These blocks are wedge-shaped through the shaft wall, resisting movement towards the interior, as shown in Figure 2. The lower halves of the ribs step towards the interior with each successive course. The middle ribs of each elevation project into the shaft approximately 6 feet, while the shallower side ribs project into the shaft approximately 4 feet 6 inches at the 500-foot level. Both middle and side ribs slope down to a six inch projection into the shaft at the 470-foot level.
Above the 500-foot level the exterior panel and rib courses become much taller, approximately 4 feet 4 inches in height versus the 2 foot height of the courses of the shaft. Above this level, the ribs take on a more vaulted nature, leaning slightly more towards the interior, between seven and ten degrees and having a horizontal joint that slopes down towards the interior, becoming “voussoirs,” or wedged-shaped stones that makes up an arch. See Figure 3. The horizontal joints become level again above course ‘H’. The pairs of corner ribs do not reach the full height of the pyramidion. The corner ribs come together at a mitered condition that stretches from the upper portion of course E through course F. This complex miter joint also brings together the tie beams in a mitered condition. This connection is capped by a two piece cornerstone, both being 2 feet 8 inches square, and a combined 5 feet 8 inches in approximate height. The center ribs of each face continue upward beyond the shorter side ribs. The center ribs accept the smaller ends of the tie beams at course ‘F’ with a mortar and tenon joint on opposing sides of the same block. The course ‘H’ blocks of the center ribs are immediately beside the cruciform stone. This block is connected to the cruciform and to course ‘G’ below with a mortise and tenon joint. The north face of the western center rib at this course is inscribed with Thomas Lincoln Casey’s name and others who were involved in the monument’s completion. The cruciform stone is level with the previously described stones of course ‘H’. The cruciform acts as the keystone of the intersecting arches of the center ribs and has an angled vertical joint to the four surrounding voussoirs. The underside of the cruciform is engraved with the year 1884 and the inside angles of the cruciform form a curved fillet in plain view. While the cruciform acts as a keystone, it is not the highest point of the rib structure. Courses ‘I’ and ‘K’ of the center ribs continue up and terminate at course ‘K’ with a single cross lintel stone that runs east to west. The north and south center ribs key into this cross lintel stone with a vertical mortise and tenon joint that is concealed from view.
Figure 3. Rendering of the upper portion of the rib structure with the exterior panels not shown for clarity.

The seven inch thick exterior panels of the pyramidion are not self-supporting, but supported on the previously described rib structure. The connection between the exterior panels and the ribs are made at a thickened base of each panel, referred to as a knuckle. These knuckles occur alternating at the center of the panel or ends of the panel. The knuckles are lifted above the panel below, with the original intention being that the horizontal joints would remain open with a 1/8 inch space between courses. The top and bottoms of the panels are profiled to form a shiplap connection that steps up towards the interior by approximately 2 inches. This step occurs at the midpoint of the panel thickness. The typical horizontal joint is capped with the horizontal elements of the lightning protection system. A few of the exterior panels at the corners are not supported by knuckles and presumably rest on the course below. Also, course ‘A’ bears upon the 500-foot level of the shaft and is connected with a continuous mortise and tenon joint. The panels are shimmed in place with 3/32 inch lead shims that wrap the underside of the knuckles. These shims close gaps and prevent stone abrasion. Each course of the ribs has an extension that carries the exterior panel of the course above. This extension is referred to as a haunch and is the tenon to the mortise of the panel’s knuckle. The haunches are the saw tooth elements shown in Figure 4. Figure 5 shows the panel knuckles. The upper portion of this mortise and tenon connection appears to be shimmed. The lower half of the mortise and tenon connection of the haunch to the knuckle is left open. This condition is where the upper portion of the exterior panel is notched to allow the haunch of the adjacent course to reach up and meet the knuckle of the course above. The vertical joints of the exterior panels have an angled notch running their length; these vertical joints are capped on the exterior with lead tees. The vertical joints at the corner are a concealed tongue and groove connection. The panel that laps around the corner to the adjacent elevation has the groove portion of this connection. Also found in this joint is a hollow square metal member, presumed to carry elements of the lighting protection system.

The exterior panels of course 546 rest on top of the cross lintel of course ‘K’ of the rib structure, this is the last exterior panel course that is supported by the rib structure. Course 550 rests directly on course 546 and has an approximately 1 foot 7 inches wide by 2 feet 4 inches tall opening in the southern panel for access to the exterior of the monument. The lower interior edges of courses 546 and 550 have a thickened edge similar to a knuckle, although this thickened condition runs the entire width of the bottom of the panel, and is mitered on either end. The final stone course, 555 is a solid block with a bump out on the
underside. This 3,300 pound stone is penetrated through the center by the lightning protection system and is capped by an engraved piece of solid aluminum that is approximately 9 inches tall. Figure 6 shows the four elevations of the monument.

Figure 4. Left: Rendering of the pyramidion with two exterior faces not shown for clarity.
Figure 5. Right: Rendering of the interior face of the pyramidion panels showing the panel knuckles.
Figure 6. Elevations of the Washington Monument.
Pertinent Repairs

Like many monumental stone structures, repairs have been undertaken on a periodic basis to address stone masonry deterioration mechanisms. According to the 2004 HSR, major exterior restoration projects were performed in 1935, 1964, and 1997–2000.

Repairs completed in 1935 included repointing all of the stone masonry below the 150-foot level, which had already begun to show signs of spalling. It was hoped that the repointing with a softer, lime mortar would alleviate some of the spalling observed. The horizontal joints of the monument above the 150-foot elevation were reportedly in good condition, but the vertical joints had reportedly lost much of their mortar. At the pyramidion level, “all of the joints, both vertical and horizontal were caulked with a plastic pointing compound.” The monument was cleaned, and many of the stone units were repaired.

In 1964, the monument was cleaned and repaired. High pressure water was used for cleaning. Exterior joints were repointed. Small cracks were reportedly filled with epoxy resin. Large cracks were reportedly filled with a two component synthetic rubber sealant. Expansion joints were cut every ten courses, beginning four courses from the base. The monument was repointed and the exterior was waterproofed with a water emulsion silicone.

In 2000, the exterior joints of the shaft were reportedly fully repointed. Vertical joints of the pyramidion were filled with silicone sealant and lead tees. Horizontal joints of the pyramidion were filled with silicone sealant and prepared to accept the lightning protection system elements, which are located in most of the pyramidion joints.

EARTHQUAKE GROUND MOTION

On Tuesday, August 23, 2011 at approximately 1:51 PM EDT, a magnitude 5.8Mw earthquake was recorded by the U.S. Geological Survey (USGS) within the Central Virginia Seismic Zone, centered approximately 84 miles southwest of Washington, D.C. near Mineral, Virginia. The earthquake occurred at an approximate depth of 3.7 miles below the surface and was followed by several after-shocks with magnitudes that ranged between 2.0Mw and 4.5Mw. In contrast with inter-plate earthquakes that occur along relatively well-understood plate-boundaries in the earth’s crust, this event was an intra-plate earthquake, occurring at some distance away from a known plate-boundary. Due to the geology of the eastern seaboard of the Unites States (U.S.), even moderate earthquake events will usually be felt across a far wider region than an earthquake of equivalent magnitude in the west, shaking an inventory of buildings that tends to be significantly older than the building stock in seismic zones in the west and, therefore, generally designed to resist far smaller earthquake forces. The USGS is now reporting that this event was the most widely-felt earthquake in U.S. history.

There are a number of scales that are commonly used to describe the size, magnitude, and intensity of an earthquake. Magnitude is a measure of the energy release associated with an earthquake at its source, and can be measured in a variety of ways. The more commonly recognized Richter magnitude is measured using a logarithm of the amplitude of waves recorded by seismographs, while Moment magnitude is based on the area “slip” along a fault. The Modified Mercalli Intensity (MMI) scale is a measure of the effects of the earthquake in any given locale. While a given earthquake typically has only a single magnitude value associated with it, a Modified Mercalli Intensity level can be assigned to each and every location in a shaken region. The MMI scale narratively describes both the range of human perceptions associated with locally felt ground shaking, as well as the effects of the ground shaking on the built environment. For example, the recent earthquake that was recorded at 5.8Mw corresponded to a shaking
intensity at the epicenter of “VII” on the MMI scale, which is described as “Damage negligible in buildings of good design and construction; slight-to-moderate in well-built ordinary structures [and]; considerable damage in poorly built or badly designed structures, [with] some chimneys broken.”

In addition to the MMI scale, the intensity of locally felt ground shaking can also be measured by instruments which record the acceleration of the ground during an earthquake event, thus allowing the shaking intensity of a seismic event to be quantified by measurable data if a recording instrument exists in the locale of interest. While there is undoubtedly a relationship between the acceleration of the ground during an earthquake and the damage caused to buildings by ground shaking, the precise relationship cannot be well-defined because the effects of the earthquake in part depend on the type, configuration and quality of the buildings being shaken. The maximum acceleration of the ground, or “Peak Ground Acceleration” (PGA), is commonly used by engineers to characterize the local intensity of shaking during an earthquake, and can be loosely correlated to the MMI scale using the “Instrumental Intensity” (Imm) map available from the USGS and referred to on their website as a “ShakeMap”. As of this writing, we are unaware of any published recordings of ground acceleration measured in Washington DC during the August 23 earthquake. However, in the absence of that data, the ShakeMap (Figure 7) provides some basis for estimating a range for the PGA in Washington DC during the recent seismic event. From the map, it can be seen that the PGA estimated for Washington DC would correlate roughly to a “moderate” level of perceived shaking and a “very light” potential for damage. However, the aspect ratio and manner in which the Washington Monument was originally constructed may have rendered it uniquely vulnerable to ground motion associated with an earthquake.
Figure 7. USGS Shake Map of August 23, 2011 for the Mineral, Virginia earthquake. Arrow shows WAMO site.
OBSERVATIONS

Cracking of Marble Pyramidion Panels

Cracking of the marble stone units which enclose the pyramidion is one form of distress observed following the earthquake. While thirty pyramidion panels were known to have cracks prior to the event and were noted in the documentation associated with the 1999 repair project, new cracking at a number of panels developed as a result of the earthquake. One of the most visible of the panel cracks occurred on the west elevation. A photograph taken by U.S. Park Police by helicopter shows the affected unit, which is located on course ‘G’ of the pyramidion (Figure 8).

![Cracking of marble panel unit at course G, west elevation of the pyramidion. (stone # W.529.2)](image)

This crack, which measures approximately one inch in width, extends through the full seven-inch panel thickness and spans the full panel height of 4 feet 4 inches. An interior view of the panel unit shows that there has been rotation of the panel unit; the top edge of the panel has moved inward and is currently restrained from moving inward more by its bearing against the knuckle of the panel above (Figure 9). Similar cracking and rotation of the marble panel units, which resulted from the earthquake, can be observed on the other faces of the pyramidion (Figure 10).
Figure 9. Interior view of crack at course G, west elevation of the pyramidion with red arrows indicating the crack, green arrows indicating the knuckles, and a blue arrow indicating the rib. (stone # W.529.2)

Figure 10. Rotation of cracked panel at course ‘G’ on the south elevation of the pyramidion. (stone # S.529.2)
To understand the issue of cracking of the marble panel units, it is helpful to consider the geometry of the exterior pyramidion panels; a diagram of a typical marble panel is shown in Figure 11. While the majority of the panel is approximately 7 inches in thickness, portions of the panel are much thinner. The upper and lower edges of the marble panels are carved into a shiplap that occurs at the midpoint of the panel thickness depth and steps up approximately 2 inches on the interior side. The horizontal pyramidion panel edges are not intended to bear on each other, and are not mortared. Thomas Lincoln Casey called for these surfaces to be shiplapped to help prevent water ingress into the monument, and for there to be approximately 1/8 inch between these surfaces to allow for expansion of the stone without inducing stresses from one panel bearing on the other. The panels are, with few exceptions, supported by the ribs units. The lower portion of each panel has a “knuckle” which protudes from the back face of the panel and bears on the rib unit. The knuckle is shown with a red arrow in Figure 11. The upper portion of the marble panel has a recessed portion which is carved into the panel to allow the rib unit which supports the panel unit above to let-in to the panel. From viewing the upper recessed area, shown with the blue arrow of Figure 11, it is clear that the reduced thickness of the marble panel increases the liklihood for crack initiation within this region of the panel, if subject to to excessive demands.

Figure 11. Diagram of typical pyramidion panel.

A diagram that shows the corresponding view of panel support is shown in Figure 12. The blue arrows showing the panel recess in Figure 11 match the rib which recesses into the panel to support the panel above, as indicated with the blue arrow in Figure 12. The knuckle, shown with the red arrow of Figure 11, is supported on the rib projection indicated with the red arrow of Figure 12.
Another view of the panel knuckle, this view from below the panel knuckle looking up (Figure 13), shows the shiplap condition at the bottom edge of the panel and a view of the surface where the panel knuckle bears on the rib. The panel cracking observed tends to occur through the upper panel recess, shown with the blue arrow of Figure 11, and extends the full height and thickness of the panel, as shown in the photograph of Figure 9.

Locations of through thickness panel cracking were documented on survey sheets to assist in the development of repairs. When possible, existing cracks in pyramidion panels that had been repaired were examined to determine if these had re-cracked. One panel was observed to have re-cracked. In addition, some panels exhibited exterior cracking that did not extend through the full thickness of the panel.
Historic Cracking of Pyramidion Panels

As noted above there were thirty panels that exhibited cracking of some form on the pyramidion that was documented in the 1999 repair project. These panels were inspected during the roped-access survey and were found in varying conditions. Many historic cracks were found to have developed beyond the extent of their previous repairs, or exhibited additional cracking or spalling within the vicinity. One panel was found to have cracked from top to bottom along a historic crack. The top of this panel is shown in Figure 14.

![Figure 14. New crack along a historic repair. Note the crack occurs along the length of the sealant as well as through stone. This stone is located on the east face of course ‘A’ (stone # E.504.15).](image)

Spalling of Pyramidion Panels

Another form of earthquake-related damage to the marble panels of the pyramidion that was observed during the exterior roped-access survey is spalling of the corners of the panels. When the panels shifted as a result of the lateral earthquake load, the corner of the panel sometimes cracked, producing a spall. One spall removed during the exterior survey is shown in Figure 15. In this particular case, the lead tee, located in the vertical joint between panels was dislodged from the joint to allow the spall to be removed. Locations that experienced earthquake-related spalling, as well as previous spalls to the extent recorded, were documented on survey sheets. The spall shown in Figure 15 is the largest spall that was removed from the pyramidion. The majority of corner spalls were similar in nature to what is shown in Figure 16.
Figure 15. Spall removed from north face of pyramidion, course ‘C’ (Stone #N.513.3).

Figure 16. Spall before removal from south face of pyramidion, course ‘E’ (stone #S.521.4)
Complex Spalling at Pyramidion Corners

In addition to the spalls that were found in the corners of pyramidion panels, there are a significant number of panels that exhibited spalling at the corners of the pyramidion. These spalls were often much larger than the typical panel corner spalls, and in contrast cracked along two faces of the stone thus wrapping around the pyramidion corner. These spalls were often associated with deformations or disconnections in the corner rods of the lightning protection system. The rods often acted as a restraint that prevented these larger corner spalls from falling out during or after the earthquake. The corners of the pyramidion are particularly susceptible to spalling due to the nature of the panels’ construction. The previously discussed shiplap connection of the panels’ horizontal joints terminates at the corners where there is also a vertical tongue and groove connection coplanar to a square hollow section metal member. This tight interlocked connection places the panel that wraps the corner under lateral forces in multiple directions. Should the course below or beside the panel move, the displacement of the upturned lip of the shiplap creates a spall, as seen in Figure 17.

![Figure 17. Spall at southwest corner of pyramidion at course ‘H’ (stone # S.534.1)](image)

This form of complex spall was also observed to have occurred at a previously repaired location. The repair was the re-installation of the spalled corner with a threaded connection. A small new spall was observed adjacent to the threaded connection on the larger anchoring stone. Backer rod was also visible in the opened joint. (Figure 18)
Cracking at Rib Bearing Haunches

Another type of damage observed at the pyramidion level is cracking of portions of the rib units, which serve as the vertical supports for the exterior marble panels. As described under the section on panel cracking, the bearing haunch of marble rib units are recessed up into the panel “knuckles.” A thin (3/32 inch) lead sheet is often visible between the knuckle and the bearing haunch of the rib unit. These lead sheets, which are relatively soft, likely allowed the panels to be more easily and uniformly set on the bearing haunches of the ribs during initial construction.

The cracking of one of the rib bearing points on the center rib of the east elevation of the pyramidion is shown in Figure 19. A shallower cracked bearing surface is shown in Figure 20. When the exterior pyramidion panels displace in the out-of-plane direction, the projecting bearing haunch of the rib stone is subject to tension. Marble has very little tensile capacity and cracking is likely the result of excessive tensile force applied in this manner. From observing a number of cracked rib bearing haunches, it appears as though only portions of the bearing surface are cracked, not the full bearing width of the rib member, which is 12 inches. The partial width cracking may be the result of the panel not bearing uniformly on the rib unit below. Additional survey work at the interior of the pyramidion is needed to determine the exact quantity and extent of cracks at the rib bearing surfaces. However it is known that there are cracks of this type on ribs at each side of the pyramidion, and through observation of interior photographs approximately one third of all visible haunches exhibited some degree of cracking.
Figure 19. Spalling of bearing haunch of course ‘G’ on east elevation center rib.

Figure 20. Spalling of rib bearing haunch of course ‘G’ on north center rib.
Spalls below Keystone of the Pyramidion

A large spall was generated directly below the cruciform shaped keystone of the pyramidion in the ‘H’ course of the southern middle rib, as shown in Figure 21. This spall when removed was over 200 pounds in weight. This spall runs the entire length of the interior face of the rib stone and is approximately 3 feet long by 1 foot wide. The upper length of this spall has revealed the mortise and tenon connection to the cruciform stone.

Figure 21. Rib unit at course ‘H’ of center rib on the south elevation, where center rib meets the cruciform keystone.
Cracking of Tie Beams

The majority of the tie beams in the ‘F’ course of the pyramidion experienced vertical cracks at their connections to the center rib units. The details of the connection of the tie beams are not known from the currently available existing documentation, which does not describe this connection. From visual observations it is suggested that the tie beams notch into the rib stones at these locations. Six of the eight connections of this type were found to have vertical cracking, with many of those tie beams also exhibiting cracking across the top face of the tie beam at the intersection of the center rib. This typical cracking is shown in Figure 22. The two tie beam connections not observed to have cracks oppose each other on the north elevation’s center rib.

Figure 22. Fracture of tie beam at course ‘F’ located east of the center rib on the south elevation. The top face of tie beam is to the right of the photo with the arrow indicating a vertical crack on the side face.
Displacement of Structural Elements within the Pyramidion

There are signs of lateral movement throughout the upper shaft and pyramidion structure of the monument. This movement is visible in the exterior panels at the vertical joints that are capped with lead tees as seen in Figure 23. In many locations this tee has a wavy appearance due to the movement of the panels, and the tee no longer covers the vertical joint. As previously discussed, the panels are supported by the ribs within, so signs of movement on the exterior indicate movement within. There are indeed multiple locations where lateral movement has occurred between courses of the structural ribs of the pyramidion. The majority of these instances occur between horizontal joints near the observation level. These joints have shifted laterally in-plane in relation to the shaft walls. It is less likely that the ribs would displace towards the interior or exterior as their angled shape through the shaft wall resists their movement towards the interior, and they are connected with cramps into the adjacent shaft wall stones. A typical lateral offset of a rib unit is shown in Figure 24.
The other form of significant displacement that was observed in the pyramidion structure was displacement at the southwest cornerstone which caps the two corner ribs. The cornerstones at course ‘G’ are comprised to two separate blocks. One is much smaller, approximately 1 foot 6 inches in height, and sits directly on top of the mitered ends of two tie beams and the two mitered corner ribs. The upturned ends of the rib stones in course ‘F’ prevent this lower of the two corner stones from moving towards the exterior of the structure. The much larger upper portion of the cornerstone is approximately 4 feet 2 inches tall. This larger portion of the cornerstone has displaced in relation to the smaller stone below. The displacement was observed to be one inch towards the south and one half of an inch to the west. The displacement between these two stones is shown in Figure 25. The location of this displacement on the interior strongly corresponds to corner spalling and displacement on the exterior panels in this location. Figure 26 shows the location of exterior damage in relation to this displaced cornerstone.
Figure 25. Base of southwest cornerstone with arrow indicating direction of displacement of cornerstone above.

Figure 26. View of the southwest cornerstone with colored arrows indicating locations of corresponding damage observed on the exterior. Blue arrow - south course G shown in Figure 10. Red arrow - complex corner spall of course H shown in Figure 17, and Green arrow - west course G shown in Figure 9.
Shaft

Gaps admitting daylight were observed in the shaft walls above the 450-foot level. An example of this is shown in Figure 27. This level of the monument is where the shaft wall transitions to a single Wythe thickness of marble blocks. Gaps at this level are much more susceptible to water infiltration due to the single Wythe construction. Gaps between blocks are not however localized to this area. Gapping of vertical joints often corresponds to cracks that propagate along these joints as well as traveling through adjacent courses of stone. This is an issue that was present before the earthquake event. As seen in Figure 28 on the west face of the monument below the 450-foot level, this crack has been previously repaired and has re-cracked. The new cracks are occurring at times along the historic repair and at times alongside the previous crack resulting in failures in the stone or in the sealant.

Figure 27. Left: daylight through vertical joint above 450-feet level.
Figure 28. Right: Re-cracking of repaired vertical joints on west elevation.

Lateral movement was observed in the upper portions of the monument shaft. One quarter of an inch per course offsets were observed at multiple courses on both sides of the southwest corner just below the 500-foot level. This displacement is visible in Figure 29 looking up at the southwest corner from the western face of the monument. The condition of mortar varied with large amounts of loss in joint mortar above the 450-foot level and below the 160-foot level. Cracking and spalling in the shaft followed the same trend being more significant above the 450-foot level and below the 160-foot level. Cracks and spalls were more prevalent towards the corners of the monument and varied in size. Cracking was more prevalent on the east face of the monument below the 450-foot level. Spalling at the top of the shaft is shown in Figure 30.
Figure 29. West face of the upper heights of the shaft with red arrow highlighting open vertical joints, and green arrows indicating successive lateral offsets in courses.

Figure 30. Full depth spall on west elevation near the pyramidion (stone #W.496.6).
RECOMMENDATIONS FOR REPAIR

Recommendations for repair are given to address the damage that was observed. Repair types and quantities that underlie the recommendations are based on observations of earthquake damage performed to date on the interior and exterior of the Monument. A detailed survey of the interior of the Monument will be required to better quantify damage types and quantities, and to design repair details. The types of repairs included in the recommendations are intended to restore the strength of damaged elements, where appropriate, and to address cosmetic and durability issues. The repairs do not address seismic strengthening or upgrading of existing elements.

The repairs types are general in nature. Investigations and analyses into the specific properties of the materials and their configurations will be needed to develop repair details that will address the full range of conditions that exist.

Cracking of Marble Pyramidion Panels

Cracking of the marble pyramidion panels results in two conditions: 1) a marble panel that is no longer one stone unit, but instead has fractured into two pieces, and 2) a panel that is prone to water leakage through the crack in the exterior face. Repairs are recommended to correct both of these issues.

To restore the integrity of the panel, all sealant should be removed from the cracked surfaces and perimeter of the panel, and both pieces of the marble unit should be carefully moved from their rotated positions into a position as close to the pre-earthquake position as possible, consistent with the offsets that may be present in adjacent stone units that are impractical to be moved. A structural connection should be added to the inside face of the panel. This connection could consist of a stainless steel plate that would span over the cracked region on the inside face of the marble panel and be fastened into the marble panel with stainless steel anchors. In consultation with a conservator, materials other than stainless steel plate, such as Fiber Reinforced Polymers (FRP) could be considered, to determine if there are advantages to their use. The structural connection will allow the panel to function as one unit, and restore the panel’s ability to bear on the rib, as intended by the original design.

To reduce the potential for water leakage through the crack in the panel, the panel crack should be sealed. Materials and methods of sealing should be selected in consultation with a conservator. A testing program may be beneficial to aid in the selection of materials.

Spalling of Marble Pyramidion Panels

Spalling of pyramidion panels should be repaired by trying to salvage the spalled material and re-insert it into position. Spalls should be fastened to the substrate using stainless steel anchors or alternatively, smaller wedge shaped spalls may be able to be set in mortar and fastened with a restraining device to prevent the spill from dislodging. Where spalled material is too fractured or deteriorated to be re-used, new marble Dutchmen, carefully selected for a good match to the surrounding stone, should be installed. Larger spalls that appeared stable during the exterior roped-access survey should be fastened into position to provide positive anchorage to the substrate.

Cracking at Rib Bearing Haunches

The portions of the marble rib units that serve as bearing surfaces for the support of the exterior marble panels experienced cracking. The cracking of the rib bearing haunches may prevent or reduce the ability of the rib to support the panel, which violates the intent of the original design. If the bearing is
compromised, the weight of the panels at the cracked bearing connection is forced to bear on the panels below it (a free space of 1/8 inch for expansion was specified in the original design of the monument). For each cracked rib bearing connection, where the bearing is believed to have been significantly reduced, stainless steel plates should be connect the panel directly to the rib, to bypass the cracked material at the rib haunch. If there is sufficient bearing area at the outside edges of the panel knuckle, a plate should be installed here to provide a means of connection to the newly installed rib plate. If there is not sufficient bearing area under the knuckle, plates should be installed and fastened to the panel on each side of the panel knuckle. All plates and anchors should be constructed of stainless steel.

Spalling of Stone at Interior of Pyramidion

A large spall was generated directly below the cruciform shaped keystone of the pyramidion in the ‘H’ rib course of the pyramidion. In addition, numerous minor chips and spalls were generated where marble units abut each other. Repair of the large spall in the pyramidion rib stone adjacent to the keystone is not recommended since it may weaken the intact portions of that rib stone.

Cracking of Tie Beams at Interior of Pyramidion

The majority of the tie beams in the ‘F’ course of the pyramidion experienced vertical cracks at their connections to the rib units. Little is known about the tie beam to rib connection, except that these are thought to contain a mortise and tenon joint (the connection is concealed from view). Recommended repairs include providing a supplemental connection capable of transferring shear and tension forces. These connections could consist of a tie beam seat, constructed of stainless steel plates that would be anchored to the rib unit. Stainless steel threaded rods would be drilled through the rib unit and attached to each end of the tie beam with plates and anchors to provide for tensile capacity. Very little documentation exists regarding the support of the tie beams at the cornerstones. A spall was observed at one of these connections and a supplemental bearing support is recommended for these tie beam connections, to insure that bearing is adequate for the tie beam to cornerstone connections at these vulnerable locations.

Displacement of Cornerstone and Rib Units at Pyramidion

The southwest cornerstone at the ‘G’ course experienced a permanent lateral offset of approximately one inch, relative to the stone unit of the rib in the course below. Other marble rib units also exhibited permanent offsets. Original design documentation indicates that there were mortise and tenon joints between the rib units of the pyramidion, therefore, visible offsets in the rib units are likely indicative of failure of the tenon of the upper unit. Re-aligning an offset unit is not practical, but the shear capacity of the rib tenon could be repaired by adding an inclined stainless steel epoxied dowel across the horizontal rib joint. Additional research or nondestructive testing will be needed to better understand the tenon capacity that has been lost, and therefore would be appropriate to restore.

Stone Masonry Joints of Pyramidion

The vertical joints of the stone masonry have been damaged, as a result of displacement of the rib structure and panel units of the pyramidion, and are allowing water infiltration into the interior of the Monument. The vertical joints are currently filled with sealant, and covered with a tee-shaped joint cover of lead. The horizontal joints of the pyramidion are typically filled with sealant and also have metal components of the lightning protection system recessed into the outside face of the horizontal joint. In order to obtain competent seals for the vertical and horizontal joints of the pyramidion, it is recommended that the lead tee-shaped joint covers and lightning system be removed from the joints, the joints cleaned and filled with new sealant. New lead tee-shaped joint covers are not recommended.
Lightning Protection System

Components of the lightning protection system were damaged as a result of earthquake-related displacement of the underlying stone units to which they were attached. The lightning protections system should be removed, damaged components repaired, and the system reinstalled into the horizontal joints of the pyramidion to allow for new sealant at the horizontal pyramidion joints.

Damage to Joints of Shaft

Many of the horizontal and vertical joints of the shaft of the monument were observed to have cracked and missing mortar in the joints. The loss of mortar was particularly acute at the upper reaches of the shaft (levels above 450-feet). Missing and damaged mortar joints allow water infiltration into the stone masonry, accelerating deterioration of the marble through freeze-thaw damage. Repair of cracked, missing and deteriorated mortar joints is recommended by removing the existing mortar and repointing the affected joints.

Damage to Elevator Components

The elevator was not studied in detail for this assessment. The elevator rails and framing should be inspected and repaired as needed prior to operation. The counterweights were noted to have shifted in the earthquake and one of the bolts holding them together had failed. At a minimum, the counterweights should be realigned and the failed bolt or rod should be replaced.

RECOMMENDATION FOR SEISMIC STUDY

Because of its configuration, construction materials, and age, portions of the monument may be vulnerable to damage from earthquakes. We recommend that a preliminary seismic evaluation be performed to assess whether there are any substantial seismic vulnerabilities. If this preliminary evaluation indicates the existence of possible significant deficiencies, a detailed seismic evaluation of the monument and seismic strengthening may be necessary. A detailed seismic evaluation would consider site-specific hazards that take into account local soil conditions and seismicity as well as a more detailed consideration of the seismic response and performance of the monument.