# “THEN THE EARTH SHOOK AND TREMBLED…” THE WASHINGTON NATIONAL CATHEDRAL IN THE AFTERMATH OF MINERAL

Matthew C. Farmer[1] and Cortney L. Fried[2]

**ABSTRACT**

Among the numerous sites impacted by the Mineral, Virginia earthquake on August 23, 2011, the Washington National Cathedral sustained some of the most significant, visually striking, and potentially dangerous damage. The Cathedral is a 100 year old unreinforced stone masonry structure in the Gothic Revival style characterized by carved stone flying buttresses, cantilevered spires, pinnacles, and its 300 foot central tower. A number of these elements partially collapsed or shifted during the earthquake. The prevalence of damage raised immediate and longterm safety concerns. Once imminent falling hazards were removed or stabilized, the great costs of accessing and repairing these elements brought to the fore fundamental questions about whether work should be confined to the damaged elements, whether only the damaged elements or all similar elements should be strengthened, and how best to develop practical criteria for strengthening that reflected the limited funds available and the future risk of significant seismic activity. Given the magnitude and complexity of the Cathedral structure, simple and direct seismic assessment approaches were needed to evaluate the dynamic characteristics of the damaged elements and measure the reliable existing capacity of these elements. The assessments relied on small scale analytical models of the significantly damaged ornamental elements to calibrate the actual damage relative to the shaking at the site, and thus back into the transfer functions for the ground level accelerations to estimate the forces at these elements. The models provided an understanding of critical portions of this complex unreinforced masonry structure with respect to earthquake behavior without development of a more complex global model that would have itself introduced many uncertainties. This paper summarizes the initial engineering response, temporary stabilization measures, assessment methodology, and the restoration program to address the range of deficient conditions identified at this historic national monument.

[1] Principal, Wiss, Janney, Elstner Associates, Inc., 2751 Prosperity Avenue, Suite 450, Fairfax, VA 22031
[2] Senior Associate, Wiss, Janney, Elstner Associates, Inc., 2751 Prosperity Avenue, Suite 450, Fairfax, VA 22031

Farmer, M.C, Fried, C.L., . Then the Earth Shook and Trembled…Washington National Cathedral in the Aftermath of Mineral. *Proceedings of the 10th National Conference in Earthquake Engineering*, Earthquake Engineering Research Institute, Anchorage, AK, 2014.

# “Then the Earth Shook and Trembled…” The Washington National Cathedral in the Aftermath of Mineral

Matthew C. Farmer[3] and Cortney L. Fried[4]

## ABSTRACT

Among the numerous sites impacted by the Mineral, Virginia earthquake on August 23, 2011, the Washington National Cathedral sustained some of the most significant, visually striking, and potentially dangerous damage. The Cathedral is a 100 year old unreinforced stone masonry structure in the Gothic Revival style characterized by carved stone flying buttresses, cantilevered spires, pinnacles, and its 300 foot central tower. A number of these elements partially collapsed or shifted during the earthquake. The prevalence of damage raised immediate and longterm safety concerns. Once imminent falling hazards were removed or stabilized, the great costs of accessing and repairing these elements brought to the fore fundamental questions about whether work should be confined to the damaged elements, whether only the damaged elements or all similar elements should be strengthened, and how best to develop practical criteria for strengthening that reflected the limited funds available and the future risk of significant seismic activity. Given the magnitude and complexity of the Cathedral structure, simple and direct seismic assessment approaches were needed to evaluate the dynamic characteristics of the damaged elements and measure the reliable existing capacity of these elements. The assessments relied on small scale analytical models of the significantly damaged ornamental elements to calibrate the actual damage relative to the shaking at the site, and thus back into the transfer functions for the ground level accelerations to estimate the forces at these elements. The models provided an understanding of critical portions of this complex unreinforced masonry structure with respect to earthquake behavior without development of a more complex global model that would have itself introduced many uncertainties. This paper summarizes the initial engineering response, temporary stabilization measures, assessment methodology, and the restoration program to address the range of deficient conditions identified at this historic national monument.

## Introduction

On Tuesday, August 23, 2011 at approximately 1:51 PM EDT, a magnitude 5.8M*w* earthquake was recorded by the United States Geological Survey (USGS) within the Central Virginia Seismic Zone, centered approximately 84 miles southwest of Washington, DC near Mineral, Virginia. 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 generally designed to resist far smaller

[3] Principal, Wiss, Janney, Elstner Associates, Inc., 2751 Prosperity Avenue, Suite 450, Fairfax, VA 22031
[4] Senior Associate, Wiss, Janney, Elstner Associates, Inc., 2751 Prosperity Avenue, Suite 450, Fairfax, VA 22031

Farmer, M.C, Fried, C.L., . Then the Earth Shook and Trembled…Washington National Cathedral in the Aftermath of Mineral. *Proceedings of the 10th National Conference in Earthquake Engineering*, Earthquake Engineering Research Institute, Anchorage, AK, 2014.

earthquake forces. The USGS has reported that this was the most widely-felt earthquake in U.S. history.

According to the "Instrumental Intensity" ($I_{mm}$) map available from the USGS and referred to on their website as a "Shake Map", the $I_{mm}$ value estimated for Washington DC was about V, which correlates to a "moderate" level of perceived shaking and a "very light" potential for damage. This description is generally consistent with findings to date following the earthquake for many common buildings and structures in the area, and subsequent measurements of Peak Ground Acceleration (PGA) gathered from instruments in the Washington DC area correlate well with this $I_{mm}$ value; however, the configuration, and construction of the Washington National Cathedral (Cathedral) is highly atypical and rendered it somewhat more vulnerable to earthquake ground shaking than more common building stock.

## Description of the Cathedral

The Washington National Cathedral (the Cathedral), officially named the Cathedral Church of Saint Peter and Saint Paul, is a cathedral of the Episcopal Church located in Washington, D.C., the capitol of the United States. It is the sixth-largest cathedral in the world, the second-largest in the United States and the fourth-tallest structure in Washington, DC. Construction of the Cathedral spanned from 1910 to 1990. Figure 1 is an overall view of the Cathedral looking east. The Cathedral is an excellent example of the Gothic Revival style of architecture. The main structure consists of a long, narrow rectangular mass formed of a nine-bay nave with wide side aisles and a five-bay chancel, intersected by a six-bay Transept. Above the crossing (intersection of the transepts, the Nave, and the Sanctuary) is the central tower, rising 301 feet above the ground. At the north and south ends of the Narthex are two smaller towers, approximately 200 feet in height above grade. Figure 2 illustrates the relationship between principle building elements from the exterior.

Figure 1. Overall view of the Cathedral.

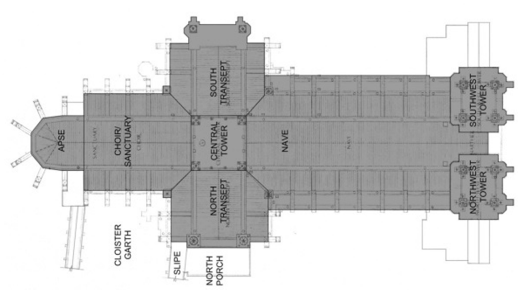


Figure 2. Overall view of the Cathedral.

## Summary of Critical Events and Activities

Due to the presence of debris on the Nave floor from the ceiling, and debris on the floors of other public spaces, one of the first priorities was relieving any risk from additional debris falling from overhead at the interior. In areas such as the side aisles of the Nave, Transept, and Choir/Sanctuary where the ceiling height is lower, a close-range survey and assessment of the vaulted ceiling, interior wall and column surfaces was performed to identify and remove any visibly loosened or otherwise potentially unstable joint mortar and limestone that existed prior to or as a result of the recent seismic event. Debris netting was installed over the Nave where methods of direct, close-range assessment were not feasible due to access restrictions. The netting extends the entire length of the Nave and the Transepts, over all areas where the public typically gathers.

Because of the unstable nature of the ornamental limestone documented in the days immediately following the earthquake, a safe perimeter was established using chain link fencing. Temporary repairs were made by Cathedral staff to repair the roof where a stone finial from the Central Tower had fallen through the batten-seam lead-coated copper roof and lodged against the structure of the overcroft above the North Transept. Similar, though less significant, roof damage caused by falling debris was similarly addressed in many locations.

A visual survey of all exterior building elements was performed from the ground, low roofs, and towers. This effort identified unstable elements and their locations to perform in-situ stabilization, locate overhead protection, assess the extent of damage, and prioritize future restoration efforts. A close-range visual condition assessment and sounding of the Northwest Tower and Southwest Tower exterior walls was performed to identify any hazardous or unstable elements along the tower shafts, and allow re-opening of the Cathedral to the general public and provide safe access through the main entrances. This work was completed using rope-access techniques and a team led by architects, engineers, and rope-access specialists.

Figure 3. Damage at Grand Pinnacle.

Temporary overhead protection and debris netting were positioned over entrances in anticipation of reopening the Cathedral prior to completion of repairs. As a result of the significant damage to the Central Tower grand pinnacles (see Figure 3), debris netting and scaffolding were installed to create a semi-permanent working platform, enabling the partial dismantling of the grand pinnacles to remove unstable elements, and provide overhead protection in case additional pinnacle components become unstable prior to restoration (see Figure 4). Scaffolding was also erected around the turret at the southwest corner of the South Transept to enable dismantling of the upper portion

Figure 4. Platform and temporary protection at the Central Tower.

of unstable stonework by Cathedral Mason staff. The lower colonnade portion of the turret was unstable but not accessible without completely dismantling the turret. Shoring was installed within the colonnade to provide increased stability until more permanent repairs are performed.

## Summary of Distress

Damage to the exterior of the Cathedral resulting from the earthquake is widespread. The majority of the damage observed during our survey is at non-structural and largely ornamental, but very heavy, sections of limestone. The damage ranged from a loss of entire courses of limestone from the grand pinnacles at the Central Tower to minor spalling and chipping at joints between stone masonry units. The damage documented following the earthquake, was sorted into three categories based on the severity of the damage and the extent of in-situ stabilization, repair, removal, or reconstruction that will be required. The first category is “No Damage” (shown in green) and illustrates areas where no visible damage was observed and that will not require any scaffolding or similar means of access for repair. The second category is “Minor Damage” (shown in orange), which consists of limestone elements that contain visible damage at the exposed surfaces of the stone but remain materially intact and fully engaged to the structure. Repair of these elements, which in several locations include surfaces and features that do not contribute significantly to the architecture of the Cathedral, can be undertaken on a more voluntary basis as funding becomes available. The final category is “Major Damage” (shown in red) and includes: missing or otherwise visibly unstable elements that remain a potential fall-hazard, and damage considered structurally insignificant but in need of immediate repair to restore the originally intended architectural expression of the element. Areas identified as “Major Damage” will require pipe-scaffolding and/or the use of mobile cranes that can facilitate the removal, replacement, and resetting of large stone pieces. The exterior damage is graphically displayed Figure 5.

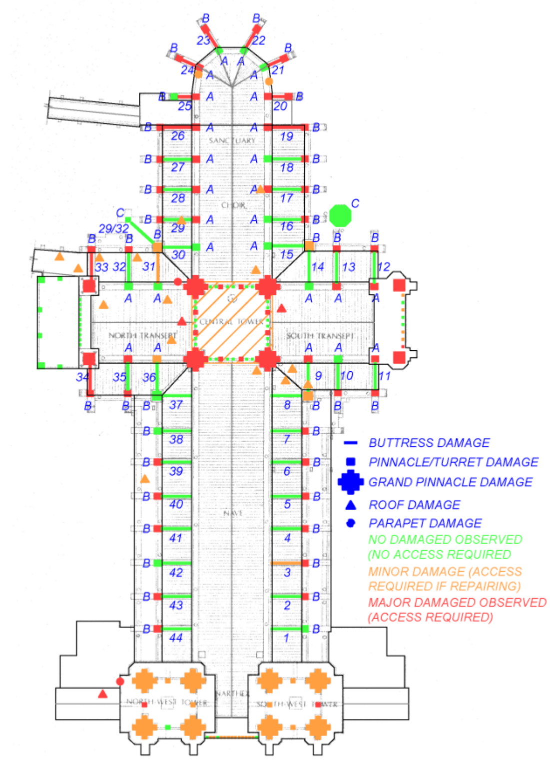


Figure 5. Summary of stone damage.

Damage at the interior of the Cathedral was limited primarily to loss of joint mortar from interior wall and vaulted ceiling surfaces, with some evidence of small chips and spalling in the adjoining sections of limestone. During this survey, several cracked and partially disengaged sections of limestone (incipient spalls) were also to eliminate potential fall-hazards inside the Cathedral. It was apparent that the damage observed at the majority of interior locations predated the earthquake; however, a significant number of fragments were further loosened or fell as a result of the seismic activity.

## Behavior of Individual Cathedral Design Elements

The pinnacles (grand, intermediate, tertiary) throughout the Cathedral structure vary in size and detailing; however, they all are typically tall and slender. Some are present at the lower elevations such as those atop the buttress piers; others are present atop the towers and occupy the highest portion of the Cathedral structure. Pinnacles are present at nearly every elevation of the structure. Construction of the pinnacles spanned from 1915 (Apse flying buttresses pinnacles) to 1990 (West Tower grand pinnacles). The earlier period pinnacles do not include any doweling between masonry elements while those built more recently incorporate bronze dowels and cramp anchors between stone masonry elements. The damage to the pinnacles consists of rotated finials, missing or damaged ornament, cracked or displaced stones, and displaced portions of the pinnacles (see Figures 6 and 7).

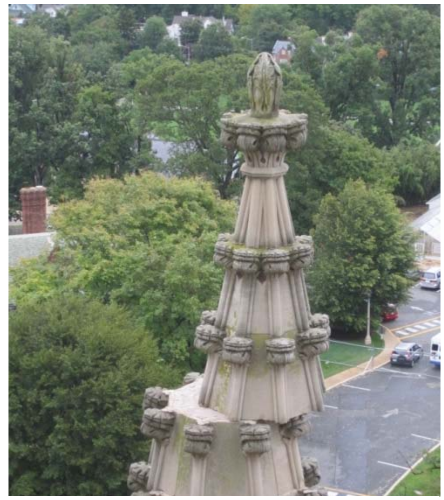

Figure 6. Displaced pinnacle.

Flying buttresses vary somewhat in geometry depending on their location within the Cathedral architecture. The buttress piers at the Nave, Transepts, and Choir/Sanctuary extend up from a low roof element where a single quadrant arch (flier) extends to the Cathedral wall. The buttress pier of the flying buttresses at the Apse extend up directly from the ground and include two fliers that span from the buttress piers to the Apse wall. Each buttress pier is topped with a pinnacle; however, a pinnacle only occurs directly above the upper flier connection at the Transepts, Choir/Sanctuary, and Apse. The flying buttresses of the Apse were previously damaged due to localized settlement that was made worse by the earthquake, likely in part due to their increased height. The apse flying buttresses were built in the early phases of construction, so the materials used and construction techniques may be inferior to the flying buttresses built later. The primary damage observed included separations between the Apse buttress piers and the fliers, as well as distress within the flier masonry (see Figure 8 and 9); however, it is believed that this damage was largely the result of buttress pier settlement that predated the earthquake.

Figure 7. Broken pinnacle.

The turrets at the South Transept are unique in that the major pinnacle is supported on an open colonnade just above the Transept roof line. The entire pinnacle shifted laterally at the colonnade that served as a “soft story” (see Figures 10). The north transept turrets do not have the open colonnade but do incorporate slender tertiary pinnacles that are supported by small “fliers” that fractured as a result of the earthquake (see Figure 11).

Figure 8. Damage at Apse buttress flier near Apse wall.

Figure 9. Damage at Apse buttress flier near pier.

Figure 10. Broken tertiary pinnacle.

Figure 11. Damage at colonnade of South Transept turret.

The metal roofs and limestone parapets at the towers and throughout the lower portions of the Cathedral suffered only indirect damage from the earthquake. The damage observed at the metal roofs and limestone parapets is largely due to impacts from stone fragments falling from the pinnacles at the towers and flying buttresses. Damage at the Cathedral interior consists of minor cracking and mortar distress, much of which predated the earthquake of August 2011. Although several small sections of limestone were removed from the Northwest and Southwest Towers during this process, the remaining surfaces of each tower were found to be structurally intact and stable, with only isolated locations of cracks, spalls, missing mortar and debonded sealant. There was no evidence of new damage resulting from the earthquake.

**Seismic Enhancement Prioritization**

When an event such as the August 2011 earthquake occurs, the natural reaction for any building owner is to consider whether the structure is adequate to resist seismic forces from a future event, or if the structure should be enhanced or upgraded in some manner to substantially reduce or potentially eliminate future damage. The answer is complicated, particularly for a monumental one-of-a-kind unreinforced masonry structure such as the Cathedral.

The most common objective of contemporary seismic engineering for most structures is not to eliminate all damage from an earthquake, but to prevent life-threatening damage and collapse. Except for those with special post-earthquake critical functions, the goal of no seismic damage of a structure during a design earthquake event is normally considered overly conservative and wasteful given the rarity of such events. Keeping that measure in mind, and assuming that the August 2011 earthquake could be characterized as a design-equivalent event, one can argue that the Cathedral met the commonly used objective of designing to prevent collapse: the overall structure remained stable with no major structural failure, and the damage sustained can all be classified as non-critical and repairable, albeit at a substantial cost due to its architectural complexity; it is a work of art rather than a simple structure. That said, much of the masonry that did fall, and much of the loosened masonry, certainly introduced risks that few engineers would consider to be acceptable.

At the moment there are no code requirements that necessitate upgrading the Cathedral structure. Without such a mandate, any seismic upgrades would be clearly voluntary as a hedge against the potential for future damage and loss of life. To make an informed decision about expending substantial costs to upgrade the structure, one should first carefully consider the risk of a future major damaging seismic event. Secondly, one should have a reasonable understanding of the physical properties and dynamic behavior of the structure, sufficient to reliably predict the effects that a major earthquake might have on the structure, the potential for injury or loss of life, what type of upgrades would be appropriate, and for what level of seismic event. None of these factors is currently well defined, so it would be premature to embark on a plan for upgrading the Cathedral, including the signature gothic design elements, in its entirety. After appropriate study, it might be found that upgrading nothing, or selective upgrading of only those portions or components of the Cathedral that present the greatest risk, is the most reasonable course of action, and that wholesale upgrading is wasteful or impossible to achieve without significantly damaging the extant historic fabric.

Given the uniqueness of the Cathedral as a treasured landmark, strengthening of all the elements that are known to be deficient by contemporary construction standards using conventional means and conservative assumptions might, of course, be prudent. However, costs associated with modifying all of the elements potentially at risk could exceed the current financial resources of the Cathedral by a large margin, and could damage much of what the upgrade would be intended to preserve for future generations. The potential for costs outstripping available funds necessitates prioritization of repairs so that any upgrades that are performed will balance cost with value, and will balance any desire to prevent crippling damage during an earthquake against the potential architectural damage that major seismic interventions can cause. A simpler, more fundamental approach should be considered with respect to addressing concerns about future seismic event similar to Mineral 2011, or other events capable of causing similar types of damage. It is suggested that prioritization of structural improvements be based on life safety, repair access, and vulnerability of particular elements to seismic forces.

The primary factor to consider in prioritizing the level of seismic upgrade is life safety, or protection of the public. Those elements at most risk of becoming a falling hazard or that are located directly above an area where pedestrians congregate should be given a higher priority for structural upgrade. For those elements that require re-anchoring as a result of the August 2011 event, upgrading could be accomplished with relatively small incremental cost if performed at the same time as other necessary repairs since access is a large percentage of cost.

Damaged elements can be found from the Narthex to the Apse, from the North Transept to the South Transept, and from the West to the Central Towers. Access to these slender elements with both labor and materials is the most challenging and most costly components of the repair work. There are many elements on the structure that are not damaged or experienced such minor distress that the cost of accessing these locations to repair and/or strengthen them does not appear to be justified economically. Therefore, access should be a key factor in determining what elements are strengthened.

The geometry and locations of many design elements employed at the Cathedral make them uniquely vulnerable to future seismic loads. As observed during our survey, the tall and slender pinnacles and Apse flying buttresses suffered the most damage during the August 2011 earthquake. Studying these elements in more depth is prudent to avoid upgrading unnecessarily but also not missing potentially serious safety issues.

## Potential Methods for Seismic Enhancements of Gothic Design Elements

There are a number of techniques for improving performance of URM structural elements exposed to seismically generated forces, most of which rely on the introduction of steel reinforcement to provide both greater connectivity between masonry elements and greater ductility to permit distortion without risk of instability. Reinforcement of some elements can be readily integrated directly into the reconstruction, for example adding dowels or vertical reinforcement between stacked stone masonry units or adding lateral anchors to secure stones to each other or to a masonry core. Other techniques can be implemented without removal of the stone masonry and installed from the exterior surfaces of vulnerable masonry elements. Provided access is available, the cost of these techniques is relatively minor when compared to that of a global restoration. But any intervention should be based on reasonable structural assumptions to determine if the modifications may adversely affect the structural behavior of the element or the supporting structural elements. For example, combining stone elements through strengthening can create larger stone elements that may create a greater hazard than the elements individually if they become unstable. One must determine if modifications provide meaningful improvement, or if they will unnecessarily damage historic features.

Based on the damage caused by the Mineral event, some characteristics of the gothic design elements require a greater level of intervention to enhance their structural performance. The fliers and pinnacles at the Apse flying buttresses, the colonnades and tertiary pinnacles at the Transept turrets, and the grand pinnacles at the Central Tower are four such conditions that could potentially benefit from more substantial structural upgrades and would otherwise be accessed to address significant seismic damage. These elements were selected for targeted analysis as part of the ongoing restoration program. At this point only the apse buttress fliers and pinnacles have been evaluated.

## Targeted Structural Analysis Modeling

Developing a computer model for the entire Cathedral was disregarded as an option due to cost, as well as the size and complex geometry of the building and the myriad assumptions and simplifications that would be required for the model to be functional. Instead, the Apse buttresses were evaluated individually to identify the behavior at the flier/pier interface and the pinnacles were evaluated further on a more detailed level to understand the damage and displacement that occurred between sections. Both efforts were dependent on detailed field verification and documentation; calibration of the models against actual damage was essential.

Following the post-event visual survey and damage documentation, one of the Apse buttresses was scaffolded to permit close-range observations and damage assessment. From this scaffolding, field measurements of the buttress components were obtained, including: changes in cross-section, pinnacle coursing, ornamental detailing, and overall massing. Information was also obtained for the pinnacles extending from the Apse clerestory.

The limited attachment to the main Cathedral structure and the separate load path to ground of the apse buttresses made modeling them individually a logical simplification, with the much stiffer apse wall also modeled as a support. A simple model in a desktop structural analysis program was created, incorporating the material properties of the stone and bulk cross-sectional changes of the buttress. The arched and tapered fliers were simplified to be prismatic elements with consistent cross-sectional dimensions and mass representing their as-built geometry. The response spectra used for the analysis was the ASCE/SEI 7-05[5] code spectra option in the software program, but modified in values to reflect the ground acceleration of approximately 0.08g documented by the USGS for the Cathedral zip code area during the Mineral event.

As expected, out-of-plane response of the buttresses governed, with limited restraint for out-of-plane movement provided by the fliers. Deflections of approximately 1-1/2 inches were expected at the upper flier/pier interface. Considering the presence of the existing settlement damage, the buttresses, reinforcement of the flier/wall and flier/pier interface was desirable to re-establish a connection between elements and limit the potential for catastrophic collapse of the fliers, but not restrain the pier from displacing (see Figure 12).

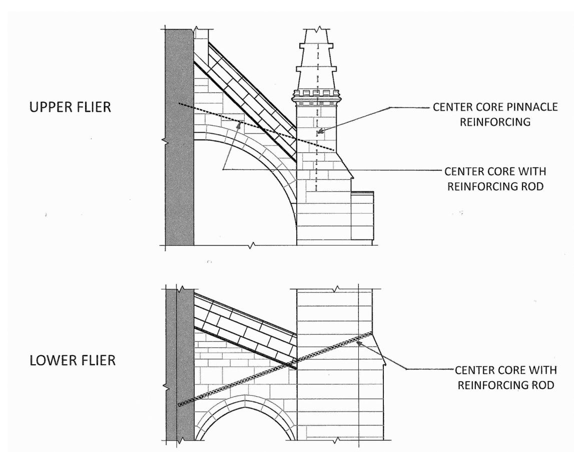


Figure 12. Apse flier strengthening.

The pinnacles at the Apse clerestory and buttress piers are square in plan, tapering vertically and terminating at a finial. Carved ornament is present at the corners along the height of the pinnacle; gabled projections are present on the lower three courses of the Apse clerestory pinnacle. The pinnacles generally consist of five trapezoidal-shaped solid limestone courses plus

---

[5] Standards ASCE/SEI 7-05, *Minimum Design Loads for Buildings and other Structures*, American Society of Civil Engineers, Structural Engineering Institute, Reston, VA.

the finial. Several square courses below these form the pinnacle shaft which transitions to either the buttress pier or the Apse clerestory. There are no existing mechanical connections between these courses.

Damage at the Apse pinnacles consisted primarily of chipping and spalling at component perimeters in combination with rotation and/or displacement, attributed to rocking and tipping of the upper courses. The majority of damage occurred at the boundary between the second and third courses below the finial, with one location at a clerestory pinnacle shaft nine courses below the finial.

Field dimensions of the pinnacles were transferred into a computer-aided drafting program to calculate section properties and weight for the pinnacles as a whole and for combinations of coursing. Resisting moments based on the weight of each coursing combination were calculated. Assuming limited engagement of the mortar, based on its age and expected condition (weathering, loss of bond), the required minimum shear force to cause the tipping of the individual coursing combination was determined based on geometry. Using this shear force in combination with weight of the applicable stone courses, the associated acceleration to generate the tipping shear force was determined. The accelerations associated with the courses where damage was documented ranged from 0.29g to 0.33g for the buttress pier pinnacle and 0.21g to 0.25g for the Apse clerestory pinnacle, representing an amplification factor of 3 to 4 times the estimated local 2011 ground acceleration.

It was found that the accelerations required to cause damage at a given course did not vary greatly along the height of the pinnacles, suggesting that damage was as likely at the finials as the base of the pinnacles, with actual locations of damage dependent on the localized conditions of limestone and mortar at a given course. Therefore, since strengthening one or two or three of the top courses would result in increasing the hazard by increasing the weight of the element that would then be vulnerable, the strengthening concepts were extended throughout the upper portions of the pinnacles (see Figure 13).

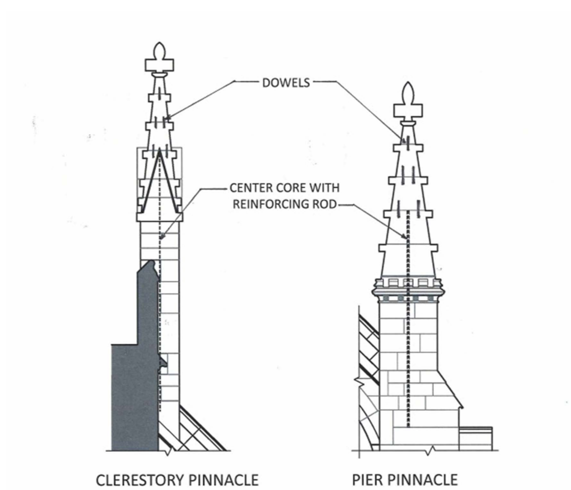

Figure 13. Apse pinnacle strengthening.

## Conclusion

The complexity of the Cathedral with respect to dynamic response, made a whole building dynamic analysis impractical. By carefully evaluating the locations of damage from Mineral, the most vulnerable elements of the Cathedral were identified and rationally analyzed to develop strengthening concepts that would improve their future performance. Prioritizing strengthening along with more conventional stone repairs by relative life safety concerns, repair access, and vulnerability to future seismic events, has provided a rational basis on which to balance future seismic risk with a repair strategy using the limited resources available.