Assessment of Earthquake Damage at the Washington National Cathedral

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Fig. 1. The Washington National Cathedral, constructed 1907–1990, 3101 Wisconsin Ave NW, Washington, D.C. 20016.

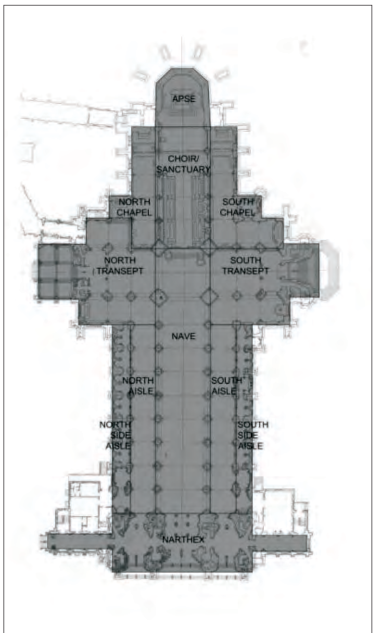


Fig. 2. Plan of ground floor interior and exterior building elements.

When project demands compete at a large-scale, historically significant project, a phased approach to documentation may provide the right compromise.

An earthquake on the East Coast of the United States is not an event to which most people would have given much thought prior 2011. But on August 23, 2011, the United States Geological Society recorded a 5.8Mw (moment wave) earthquake with its epicenter in Mineral, Virginia, 84 miles southwest of Washington, D.C. This event affected numerous structures in the area, many of which were registered historic places and landmarks or were constructed using historic materials and methods. Many more unreinforced masonry structures were damaged than modern buildings constructed of concrete or steel. The Washington National Cathedral, perhaps the largest unreinforced masonry structure in the Washington, D.C., area, suffered significant damage (Fig. 1).

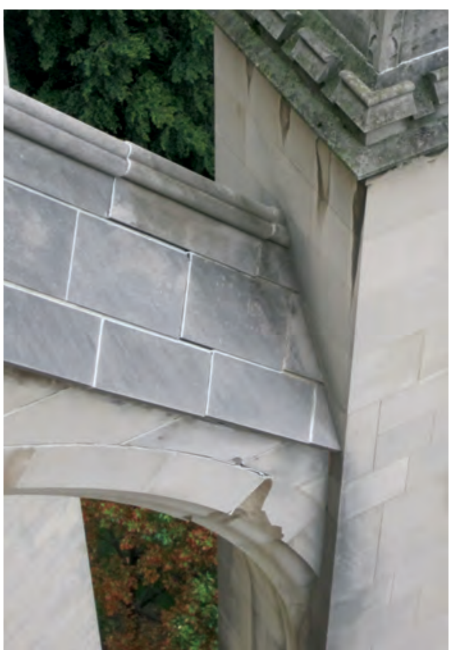


Fig. 3. Typical damage to a turret.

Fig. 4. Typical damage to a flying buttress.

Considered an excellent example of the Gothic Revival style of architecture, the cathedral is constructed principally of Indiana limestone on both the interior and exterior. The main structure consists of a narrow, 445-foot-long rectangular mass of masonry formed by a nine-bay nave with wide side aisles and a five-bay chancel, intersected by a six-bay transept (Fig. 2). Above the crossing (at the intersection of the north and south transepts, the nave, and the sanctuary) is the central tower, which rises 301 feet above grade. At the north and south ends of the narthex are two smaller towers, each approximately 200 feet in height above grade.

The design of the cathedral encompasses a mix of influences from the various Gothic architectural styles of the Middle Ages, identifiable in the pointed arches, flying buttresses, pinnacles, and turrets. The Gothic style is carried into the interior by several design elements, including a variety of ceiling-vaulting styles, the stained-glass clerestory and rose windows, and carved stone ornament. Figures 3 and 4 represent a few of the most common stylized Gothic-design elements at the cathedral that suffered significant damage from the earthquake.

Due to the sheer magnitude of the cathedral, documentation of any kind and for any purpose is a daunting task. As a result of the earthquake, however, there was an immediate need to assess and document virtually all of the interior and exterior in an effort to identify damaged elements, particularly those that posed significant life-safety risks or that were structurally unstable. This task was more challenging due to access constraints and the desire to reopen the cathedral to the public as quickly as possible.

Once the extent and severity of the damage was realized, the need for documentation to support a restoration program also became apparent. The documentation would need to include the context and relationship of all interior and exterior building elements, the specific location of each damaged element, the type of damage and repairs required at each element, the quantity of repairs, and the amount of stone to be removed to access the damaged elements. What also became clear early in the documentation process was the need for a common referencing system that addressed both element-naming conventions and element locations. The system evolved over time, based first on less formal, previously established naming conventions used by the cathedral staff, and then ultimately developing into a more formal building-wide system.

Documentation: Start with What You Have

Whenever one is faced with assessing an existing facility, a review should be performed to determine what existing documents may be of use. Construction of the Washington National Cathedral began in 1907 and continued, with a few short lapses, until 1990. The level and detail of construction documentation varied with the portions of the building being constructed. Unfortunately, there were very few drawings on site after the earthquake; most construction drawings had been moved off site to an archival facility several years earlier. The archival-facility staff were not accustomed to cataloguing construction drawings, so the documents were not organized or referenced in a way that allowed them to be searchable. As a result, a treasure trove of original documents was largely inaccessible for this project.

Initial Post-earthquake Assessment

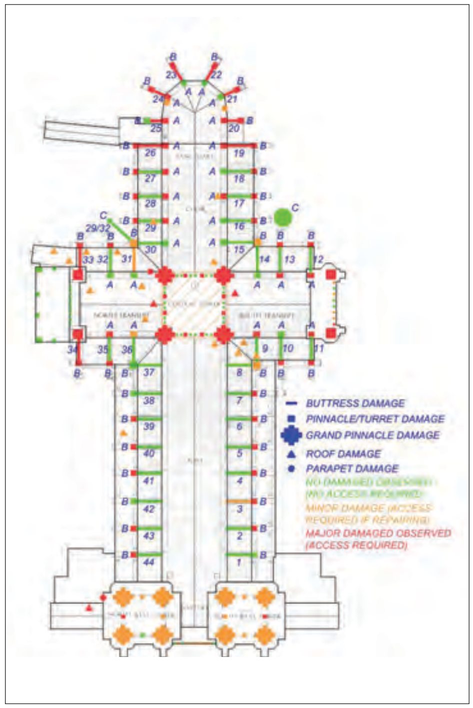
Within a few weeks of the earthquake, an initial review of the resulting damage was conducted in order to establish priorities for limiting future damage and ensuring public safety. Therefore, assessment and documentation of all visible damage was necessary to determine what portions could pose a safety risk. Given the limited time available, work was begun using photocopies and electronic scans of the drawings that were available at the cathedral. These were supplemented by sketches, photographs, and notes, along with tablet-based comments and photos. Using telephoto equipment, exterior assessments were conducted from the roofs and gutters, from interior spaces that afforded views of exterior elements, and from the ground. Using supplemental lighting and binoculars, interior assessments were made from the nave floor and from rolling scaffolding in the side aisles and narthex.

The first rough location-reference plan was developed from a document already in use by the cathedral's staff that organized the plan by numbering each buttress or column line in a counterclockwise direction around the building perimeter (Fig. 5). This document also served to establish common spatial-organizational references, such as the nave, apse, crossing, and transepts. What quickly became apparent was that a unified vocabulary needed to be established for the various decorative Gothic features that adorned the cathedral and its pinnacles. Visual definitions were created and distributed to the assessment team so that documentation references would be consistent (Fig. 6). Some of the common exterior features that were visually defined included finials, gablets, crockets, flyers, buttress piers, turrets, and primary, secondary, and tertiary pinnacles.

Documenting Damage over the West Entrance

As the exterior assessment continued over the next several months, it became clear that some of the vertical facade surfaces included damaged elements whose stability was more difficult to assess (Fig. 7). Many locations of concern were directly above the entrances, which increased the risk to cathedral visitors. In order to reopen the cathedral to the public without overhead protection at the west facade, a close-range survey was undertaken in an attempt to ensure that any unstable stone fragments were identified and removed or stabilized in place. Specially trained preservation-engineering teams used rope access to perform a hands-on survey of the vertical surfaces above the main west entrance, including the west facades of the west towers and all facades of the central tower. Damage was documented on digital tablets loaded with scans of the original drawings and on overlay software that enabled photo and note referencing while the engineers were suspended from boatswain chairs (Fig. 8).

During the process of documenting stone damage on the vertical surfaces, it



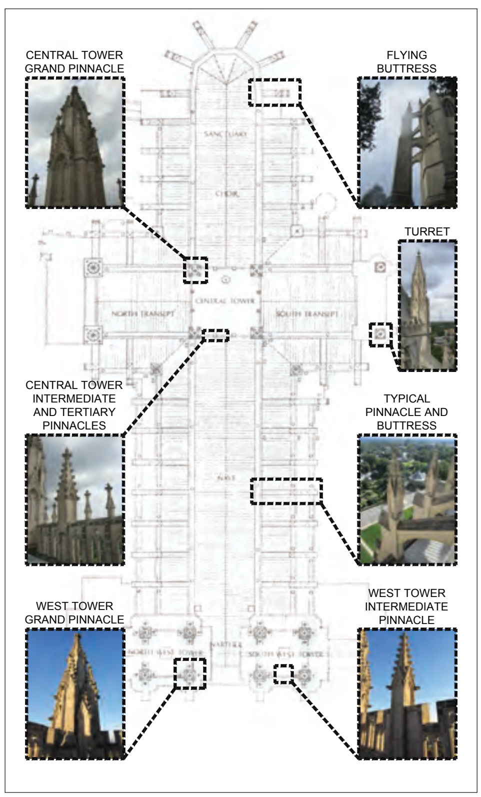


Fig. 5. Plan showing damage distribution.

Fig. 6. Visual definitions of typical elements for documentation.

became apparent that a vertical-reference datum was also needed so that specific stones could be identified for repair. The floor levels were considered but rejected because their elevation and presence were not consistent throughout the interior or at the grand pinnacles and other elements that extended beyond occupied areas. Elevation drawings that were available were reviewed to determine what the original designers used for a vertical-reference axis. That research revealed that each stone course was uniquely and consistently numbered from top to bottom on every elevation drawing, regardless of the facade illustrated or the drawing scale. The course numbers quickly became the vertical-reference datum for locating damaged stone elements.

Post-processing and Organization of Initial Assessment

Once the initial cathedral-wide damage assessment was completed in 2012, each damaged stone could be classified by the type of damage, the extent of damage, and the location of the damaged stone (Fig. 9). This information was critical not only in developing preliminary cost estimates for the individual repairs but also in determining the extent and breadth of the restoration required and the types of equipment necessary to reach each damaged stone. With a project of this scale and architectural complexity, one of the principal cost drivers was creating the access to implement repairs. Decisions about using fixed scaffolding, mobile cranes, a tower crane, swing stages, or any combination of these access methods had a significant impact on cost, as well as on the sequencing of the repair work. The ultimate goal was maximizing efficiency and minimizing project duration.

Damage to the exterior proved to be extensive. Most of the damage was concentrated on non structural and largely ornamental sections of limestone. The damage ranged from a loss of entire sections of stone from the grand pinnacles at the central tower to minor spalling and chipping at joints between stone masonry units.

Fig. 7. Typical damage to a turret.

Fig. 8. Damage caused by earthquake being documented on digital tablets by engineers while suspended from boatswain's chairs.

As illustrated in Figure 5, the damage documented was further sorted into three categories based on the severity of the damage and on the extent of in situ stabilization and repair or removal and reconstruction that was required.

The first category of damage (shown in green in Figure 5) was identified as "no damage"; this term identified those areas where no visible damage was observed and therefore did not require any scaffolding or similar means of access for repair. The second category (shown in orange) was identified as "minor damage"; it consisted of limestone elements that had visible damage at the exposed surfaces of the stone but remained materially intact and fully engaged to the structure. Repair of these elements, which in several locations included surfaces and features that did not contribute significantly to the overall architectural expression of the cathedral, could be undertaken on a more voluntary basis as funding became available. However, mobilization and erection of pipe-scaffolding or similar equipment would be required to access these locations.

The final category (shown in red) was identified as "major damage" and included missing or otherwise visibly unstable elements that remained a potential fall-hazard or damage considered to be structurally insignificant but visually important and therefore in need of more immediate repair. Areas in this category required pipe scaffolding and/or the use of mobile cranes and hand-operated block-and-tackle devices to facilitate the removal, replacement, and resetting of large pieces of stone.

All information associated with each damaged stone was input into a database that could be searched by the type of damage, the stone location, the damage category, and the general area of the cathedral.

Development of Construction Documents

When preparing construction documents for an existing building, the question often arises of whether to use existing drawings, create new drawings, or use a combination of the two. This decision is usually based on the needs of the project. Creating these documents for the cathedral presented additional requirements, such as generating cohesive drawings that could be efficiently and frequently updated for restoration work that would span multiple years and phases, as well as developing a damage-identification system independent of the phase and/or specific area.

Even having access to an archive full of original documents for this project provided its own challenges. The original blueprints that were available did not always yield clear scans when digitized. Due to limited access and quality of the actual drawings, the decision was made to draft new drawings whenever possible. This approach presented its own daunting task of providing accurate detail of a large-scale Gothic Revival building. A technology company specializing in three-dimensional (3D) scanning was employed to provide the base data for generation of the restoration documents where original drawings were not available or usable. The laser scan was able to provide a 3D point cloud, from which two-dimensional (2D) baseline drawings of elevations and reflected ceiling plans were extracted.

The 3D scan and resulting point cloud produced a large quantity of information. While 2D drawings could be generated in a relatively short amount of time, the files were enormous and difficult to work with because they were created by linking short individual line segments through proprietary post-processing software. The files also required careful review for accuracy, particularly for overall dimensions, and to reflect uncaptured field conditions. The need to perform such a significant back-check was an unwelcome surprise.

Once the large-scale drawings were vetted, enlarged views of specific elements were generated by internally referencing the baseline drawings. The decision to internally reference the baseline drawings and not to generate additional unique drawings was made for two main reasons: referencing one master file eliminated the need to update drawings in multiple locations during later revisions, and it reduced the overall size of the drawing files by decreasing the number of individual large drawing files that resulted from the post-processed laser-scan data.

Due to the scale and quantity of repairs, a global grid system was developed based on the major structural elements in plan so that any damaged architectural element could be quickly referenced and the corresponding repairs defined. The system also enabled uniform element identification within subsequent phases of work, always referencing back to the master document set.

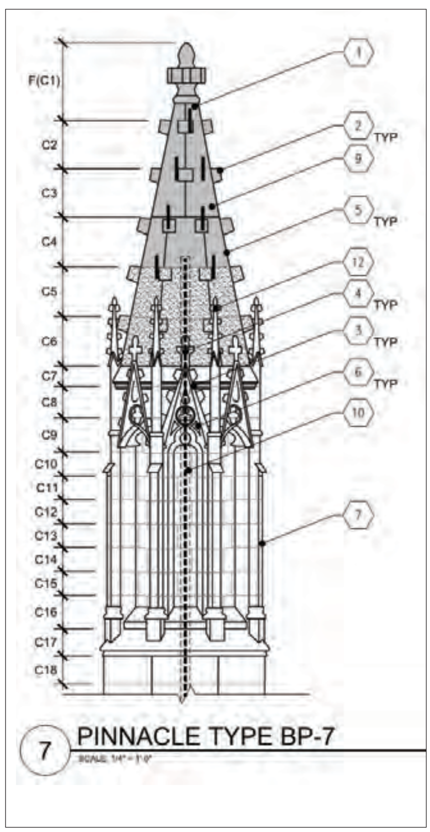
Once the restoration drawings for the entire cathedral were finalized and views of individual elements were provided, the damage documentation from the initial survey was overlaid onto the respective elements. A comprehensive damage and repair legend, with corresponding references to applicable repair details, was developed in order to provide consistency throughout the interior and exterior repairs. Specific damage locations were identified on the drawings with a combination of keynotes and graphic indicators (Figs. 10 and 11). Application of keynotes provided a space-efficient method of referencing back to the damage and repair legend. This approach required careful coordination and organization upfront, but it ultimately resulted in an accurate drawing set that could be easily divided into phases and provided to a contractor for execution of the restoration work over several years, as funding becomes available. In 2014 Phase I was bid, and the restoration work began.

Periodic Condition Assessments

Since the restoration work would be performed in multiple phases and given the likely time lapses between them, it was recommended that the original condition assessments be updated periodically (at least every five years), in order to confirm the ongoing stability of damaged elements and to identify any new damage or changes in field conditions that would warrant intervention. The restoration drawings and the initial damage assessment were combined in a proprietary software specifically designed for condition assessment of structures. Digital field-survey sheets were generated for each exterior element, referencing the global grid system and the comprehensive restoration drawings. A customized interface, which included a prepopulated

INTERMEDIATE PINNACLES

ELEMENT GRID LOCATION	ELEMENT TYPE	ELEMENT COURSE	DAMAGE-REPAIR	DAMAGE NOTES
D.6-2.5	IP-2	1	MS- IES/INS	MISSING FINIAL
		2	MS- IES/INS	MISSING STONE
		10	DP- RDS	ROTATED PINNACLE PINNACLE SHAFT
		11	DP- RDS	ROTATED PINNACLE PINNACLE SHAFT
E.3-3.5	IP-2	1	DM- PJT/SJT	DEBONDED BED JOINT AT FINIAL
		N/A	DM- PJT/SJT	DEBONDED BED JOINT
F-2.5	IP-2	1	DM- PJT/SJT	DEBONDED BED JOINT
		N/A	DM- PJT/SJT	DEBONDED BED JOINT
		N/A	DM- PJT/SJT	DEBONDED BED JOINT
		10	SP- RES/DNS/ESE/NRR	SPALL(S) AT PINNACLE SHAFT
		11	SP- RES/DNS/ESE/NRR	SPALL(S) AT PINNACLE SHAFT
E.3-1.5	IP-2	-	NO DAMAGE	



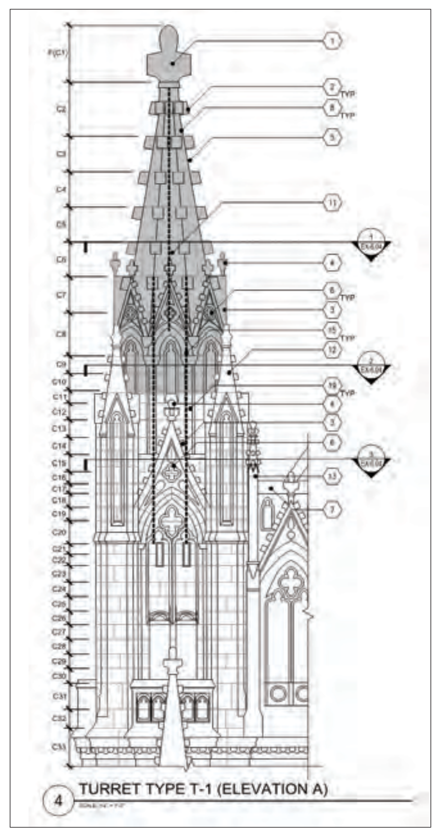


Fig. 9. Damage legend showing typical damage nomenclature generated after cathedral-wide assessment.

Fig. 10. Enlarged elevation of pinnacle used in construction documents identifying course numbering and typical elements.

Fig. 11. Enlarged elevation of turret used in construction documents identifying course numbering and typical elements

menu, was created for the digital survey sheets so that a drop-down list containing the damage and repair legend could be easily accessed in the field. It also allowed field personnel to embed photos at specific damage locations directly within the digital survey sheets.

Once the field work was concluded, the data was exported to spreadsheet software, creating a searchable database of damage. Data can be organized based on location within the global grid, stone location within the element, and damage type. Each discrete damage location was also associated with representative photographs, eliminating the need to search through massive quantities of photos during post-processing. The linking of the photos from the most recent assessment also provides a basis of comparison for subsequent surveys, eliminating the subjective nature of determining damage progression. By using the comprehensive restoration drawings as the basis for the digital survey sheets, field personnel were also able to verify attributes, such as dimensions and coursing, for each element. This provided additional authentication of the laser-scan drawings and enabled correction of discrepancies in the comprehensive restoration drawings.

In 2016 the first condition assessment was successfully executed using this adapted notetaking system. The data collected will serve as a baseline of conditions for comparison with field conditions observed during future assessments. As additional assessments are made and restoration completed, this annotative software can be modified to fine-tune the drop-down menu functions to include yet-unidentified conditions or to expedite documentation when there are no changes in element conditions. Data can also be sorted quickly to inform field personnel about conditions that have worsened or require more careful assessment. Identifying worsening conditions quickly and providing quantities that can be categorized by global location may provide beneficial data when prioritizing restoration work for future phases.

Conclusions

Like many places of worship, physical-plant needs are secondary to the mission of the Washington National Cathedral: ministering shall always take priority over maintenance. As a result, despite many generous donations from across the country, the road to restoration will be a long one in which tracking restoration progress and deferred repairs is critical. Of the $26 million projected earthquake-restoration cost, about $8 million has been raised and expended on addressing the most critical structural concerns over the past six years. As the project duration lengthens, documentation of the damage is necessary to prioritize future restoration needs and package them into manageable and affordable phases. More importantly, the damage documentation must also be sufficiently dynamic to accommodate worsening of previously observed conditions due to the passage of time and to incorporate new damage or deferred maintenance that may arise during such a long project-time horizon. In addition, the cathedral has chosen to relocate many of the original construction documents in-house for future restoration and maintenance needs.

Photographs courtesy of the authors and the Washington National Cathedral.

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