Repairing Earthquake Damage at The Washington National Cathedral

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Washington National Cathedral

Overall Length: 517 ft
Width of Nave: 142 ft
Height of Nave: 102 ft
Central Tower Height: 306 ft
West Tower(s) Height: 226 ft
Washington National Cathedral

- Cathedral Church of Saint Peter and Saint Paul
- Seat of the Bishop of the Episcopal Church
- 6th Largest Cathedral in the World
- 2nd Largest Cathedral in the US
- Highest Elevation in Washington DC
- Unreinforced Masonry Structure
- 4th tallest structure in Washington D.C.
- Occupies the highest elevation in the district
- Construction has spanned over 100 years (1907-present)
- Designated as Neo-gothic architectural style
  - Rose Windows
  - Pointed Arches
  - Flying Buttresses
  - Lots of Pinnacles...
Washington National Cathedral

Gargoyles!

and grotesques..
Washington National Cathedral
Cathedral Construction

- 1893 – Charter to erect the Cathedral was passed by the United States Congress January 6th
- 1907 – Construction began on September 29th President Theodore Roosevelt attended laying of the foundation stone
- 1912 – Bethlehem Chapel was opened to the public
- 1942-1948 – No construction due to World War II
- 1948 - 1972 – Construction of the Nave
- 1961-1964 – Construction of the Central Tower
- 1976 – Installation of the Rose Window
- 1983-90 – Construction of the West Towers
- 1990 – Last finial placed (President George H. W. Bush attended)
- 2011 – Mineral, VA Earthquake
  Decorative work on the Cathedral remained in progress at the time of the earthquake
- 2021 – Earthquake restoration work continues
Cathedral Construction
Cathedral Construction
Cathedral Construction
The Issues...

Structure Dynamics
- Towers and roof elevations of different heights
- Pinnacles and spires rising from different roofs and from buttresses of different heights
- Buttresses founded on the ground and on roofs

Condition
- Original mortar quality varied by vintage (strength, permeability…)
- Mortar weathering varies by age and exposure
- Presence of pins, types of pins and embedment of pins varies by element, by vintage, etc.
The USGS has reported that this event was the most widely-felt earthquake in U.S. history…
The “Mineral” Event

Did You Feel It?

M6.0 earthquake
Central California
Sept. 28, 2004

M5.8 earthquake
Central Virginia
Aug. 23, 2011

Stars show epicenters and dots show where people reported at least weak shaking.
The “Mineral” Event

PGA vs. Epicentral Distance
August 2011 Virginia Earthquake

- CESMD Stations
- North Anna Nuclear Power Plant

Peak Ground Acceleration, PGA : g

Distance from the Epicenter, D : km

Note: Station information such as the location of the accelerometer and soil conditions is not known.
Make Safe Operations

Interior
- Debris Netting System

Exterior
- Chain Link Fence
- Roof Repairs
- Egress Protection
Critical Events & Activities

Crane Collapse/Investigation/Removal

- September 7, 2011
- Liebherr LTM1400-7.1,400 Metric Ton Crane
- Damage to Herb Cottage
- 9/11 Services Cancelled
Critical Events & Activities

Central Tower Scaffolding of Grand Pinnacles

- Completion of Scaffolding and Protective Netting
Critical Events & Activities

DAT Survey
Survey/Documentation of Interior
Survey/Documentation of Exterior

- Identifying Unstable Elements
- Assessing Overall Extent of Damage Resulting from Earthquake
Seismic Damage

Pinnacles
Seismic Damage

Pinnacles
Seismic Damage

Pinnacles
Seismic Damage

Pinnacles
Seismic Damage

Buttresses
Seismic Damage

Buttresses
Seismic Damage

**Interior**
- Isolated locations of unstable mortar
- Limestone spalls
- Cracks in boss stone, ribs, and ceiling interface
Characterization of Structure Response

- No major structural damage
- Significant falling hazards and loss of ornament
  - Rocking response in two dimensions predominated behavior
- Assessment with respect to intensity of ground shaking
  - MMI/Imm V – Damage to Structures Not Expected
  - More Damage than Most Buildings in the Region
  - PGA generally consistent with prior historic “large” earthquakes such as New Madrid (1811) and Charleston (1886)
  - Event was likely equivalent to the MCE for shorter period structures, with a return period of 2000 to 3000 years
§ Complex dynamics with a multitude of modes (Pinnacles, Structures atop Structures)
§ Large mass associated with tall slender structures – rocking mode dominant
§ Highly variable mechanical engagement
§ Longer period elements suffered most damage
§ Reduction of P/A and sliding resistance over height of element
§ “Soft story” zones in certain local elements
Structural Seismic Characteristics
Seismic Repair Considerations

- Access to make repairs
- Address current life safety risk from falling hazards
  - Reduce risk while making repairs if incremental effort is marginal
  - Do not increase the risk!
- Assess element susceptibility to seismic forces
  - Aspect ratio/stability
  - Proximity to damaged elements
  - Demonstrable seismic response to Mineral EQ

- Phasing Repairs
  - Damage Stabilized
  - Access to Damage areas with tower crane and mobile crane
  - Funding
Repair Considerations

Phasing/Access

- Phase I – Interior Ceiling and Apse Buttresses
- Phase IIA – North Transept
- Phase IIB – West Towers
- Phase IIC – South Transept Dismantling
- Phase IID – Garth
- Phase IIE – Way of Peace & SE Turret
Repair Considerations
Criteria for discussion of whether risks presented by various parts of the Cathedral are acceptable, and under what excitation.

Analytical models for discrete Cathedral elements.

Estimation of transfer functions from roughly known ground accelerations based on existing damage to estimate future loads at discrete elements.
Repair Implementation

Engineering for Preservation

- Identify the critical vulnerabilities of the existing construction, and develop “surgical” methods of intervention to mitigate them.

- Identify/credit the positive attributes of the existing construction, and develop “surgical” approaches to leverage them.

- Take advantage of the access to the structure to target improving the future seismic performance, rather than just restoring the original construction. Consider the consequences of “repair” with respect to the potential to inadvertently increase risk.
Solid Stone courses

Brick coursing with stone veneer
Grand Pinnacles
Grand Pinnacles
Grand Pinnacles
Turrets at the South Transept
Turrets at the South Transept
Turrets at the South Transept
Turrets at the South Transept
Turrets at the South Transept
Repair Implementation

Apse Buttress Elevations
Repair Implementation

Apse Buttress Elevations
Repair Implementation

Apse Buttress Elevations

- What is the appropriate repair to damaged buttress pinnacles?
- What is the appropriate repair to damaged flyers?
- Since access is a large component of the cost of repair, what else should be recommended, if anything?
  - future risk
  - limited funds
  - historic/cultural importance
  - appearance
Gravity and Wind Forces

- Blue = gravity
- Yellow = wind
- Red = thrust from wall
Repair Implementation

Seismic Forces

- Green = Seismic
- Red = Critical section
What is the appropriate repair to damaged buttress pinnacles?

- Pins presumed absent
- Shear resistance is the lesser of bed joint
  - bond strength
  - mortar strength
  - $P \times \mu$
- Stability concern diminishes where center of mass is lower
Repair Implementation

Strengthening

= Critical section
Repair Implementation

Strengthening - Pinnacles

TYPICAL APSE
CLERESTORY PINNACLE

TYPICAL APSE
BUTTRESS PINNACLE

NEW 3" DIAMETER CENTER-CORE WITH (1)
1/2" DIAMETER TYPE 304 STAINLESS STEEL
THREADED ROD (Fy = 30 KSI, Fu = 75 KSI).
IF NECESSARY, EXTEND TOP OF ROD 6" INTO THE HIGHEST FIXED COURSE (MAY VARY). COORDINATE WITH PINNACLE COURSE REMOVAL, LOCATE ROD IN CENTER OF CORE WITH CENTRALIZERS AND FILL SOLID WITH SA-5 GROUT. SEE PINNACLE ANCHOR SCHEDULE (AP-8.01) FOR CENTER-CORE AND THREADED ROD LAYOUT.

UP TO FOUR (4) PINNACLE COURSES PLUS FINAL TO BE REMOVED, REPAIRED, CLEANED AND RESET. SEE SHEET AP-8.01.

EXTEND ROD 30" MIN. BEYOND TOP OF APSE WALL.

UP TO FOUR (4) PINNACLE COURSES PLUS FINAL TO BE REMOVED, REPAIRED, CLEANED AND RESET. SEE SHEET AP-8.01.
SEE DETAIL 1/ AP-8.02.

REMOVE RIDGE STONE TO PROVIDE FLAT SURFACE FOR ALTERNATE CORING LOCATION. TERMINATE REINFORCING AT BED JOINT OF UNIT AND REINSTALL RIDGE STONE AFTER COMPLETION OF CORING AND GROUTING.

PROVIDE ACCESS PORT(S) INTO SIDE OF FLYER OR APSE WALL TO INSTALL GROUT OR RELEASE AIR, AS NECESSARY.

OPTION 2: FLYER CENTER-CORE AND ROD INSTALLATION LOCATIONS WITH TWO (2) CORES REQUIRED FOR OPTION 2 REINFORCEMENT CONFIGURATION. NEW 3" DIAMETER CENTER-CORE WITH (1) 1 1/2" DIAMETER TYPE 304 STAINLESS STEEL THREADED ROD (Fy ≥ 30 KSI, Fu ≥ 75 KSI). LOCATE AND SECURE ROD IN CENTER OF CORE WITH CENTRALIZERS AND FILL SOLID WITH SA-5 GROUT.

UP TO FOUR (4) PINNACLE COURSES PLUS FINAL TO BE REMOVED, REPAIRED CLEANED AND RESET. SEE SHEET AP-8.01.

VERTICAL CORE PER DETAIL 2/AP-8.02. DO NOT INTERSECT WITH FLYER CORE LOCATION. SEE DETAIL 7/AP-8.02.

OPTION 1: NEW 3" DIAMETER CENTER-CORE WITH (1) 1 1/2" DIAMETER TYPE 304 STAINLESS STEEL THREADED ROD (Fy ≥ 30 KSI, Fu ≥ 75 KSI). LOCATE AND SECURE ROD IN CENTER OF CORE WITH CENTRALIZERS AND FILL SOLID WITH SA-5 GROUT.

TEMPORARILY SEAL CORE HOLE AND INSTALL AN AIR RELIEF PORT. INFILL EXTERIOR FACE OF CORE HOLE WITH NEW SQUARE OR ROUND DUTCHMAN REPAIR. AFTER GROUTING IS COMPLETE. SEE DETAIL 6/AP-8.06.
Strengthening – Lower Flyer

IN-FILL EXTERIOR FACE OF CORE HOLE WITH NEW SQUARE OR ROUND DUCHMAN REPAIR AFTER GROUTING IS COMPLETE. SEE DETAIL 8/AP-8.06.

NEW 3" DIAMETER CENTER-CORE WITH (1) 1½" DIAMETER TYPE 304 STAINLESS STEEL THREADED ROD (Fy ≥ 30 KSI, Fu ≥ 75 KSI). LOCATE AND SECURE ROD IN CENTER OF CORE WITH CENTRALIZERS AND FILL SOLID WITH SA-5 GROUT.

PROVIDE ACCESS PORT(S) INTO SIDE OF FLYER TO INSTALL GROUT OR RELEASE AIR, AS NECESSARY.

18" MIN. OR ½ WALL DEPTH, WHICHEVER IS GREATER.

TYPICAL LOWER FLYER
SCALE: 1/8" = 1'-0"
So now you’ve designed something..
Center Coring
Center Coring
Center Coring
Center Coring
Center Coring
Center Coring

Physical Property Requirements

- Strength
- Flow
- Chloride Content
- Freeze/Thaw Durability (Air Entrainment)
- Low Sulfates
- Wick Bleed
- Volume Change
Center Coring Challenges

Grout Flow/Control
Stone Restoration

North Transept Turret
Stone Restoration

North Transept Turret
Stone Restoration

North Transept Turret
Stone Restoration

North Transept Turret
Stone Restoration

North Transept Turret
Stone Restoration

North Transept Turret
Stone Restoration

Carved Stone Dutchman
Stone Restoration

“Unforeseen conditions”
Stone Restoration

“Unforeseen conditions”
Dismantling a Cathedral
Dismantling a Cathedral
Dismantling a Cathedral
Access
Access
COVID-19

- Social distancing
- Reduced crew size
- Required face coverings

Washington National Cathedral found 5,000 medical masks just sitting in its crypt
The Team
The Washington National Cathedral

Stabilization Efforts

Scaffolding and Dismantling of South Transept Turret

- Shoring of colonnade
Stabilization Efforts

Dismantling of Central and West Tower Pinnacles