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 gothic revival 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

[Diagram showing the phases of construction]

- North Transept Phase 8: 1946-1962
- South Transept Phase 5: 1946-1962
- North Transept Phase 8: 1946-1976
- South Transept Phase 8: 1946-1962
- Central Tower Phase 8: 1961-1964
- Choir/Sanctuary Phase 3: 1922-1932
- Apse Phase 2: 1915-1919

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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 “Mineral” Event

Date: August 23, 2011
Time: 1:51 PM EDT
Magnitude: 5.8Mw
Location: Mineral, VA
Depth Below Surface: 3.7 mi
Distance From Washington DC: 84 mi

The USGS has reported that this event was the most widely-felt earthquake in U.S. history...
The “Mineral” Event

Critical Post-EQ Events & Activities

Make Safe Operations

Interior
- Debris Netting System

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

Central Tower Scaffolding of Grand Pinnacles

- Completion of Scaffolding and Protective Netting

Critical Events & Activities

DAT Survey
Critical Events & Activities

DAT Survey of Central and West Towers

Survey/Documentation of Interior
Seismic Damage

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

Survey/Documentation of Exterior

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

Pinnacles

Seismic Damage

Pinnacles
Seismic Damage

Buttresses

Seismic Damage

Buttresses
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

Structural Seismic Characteristics

- 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

- 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
Structural Analysis

- 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.
Grand Pinnacles
Grand Pinnacles

Grand Pinnacles
Turrets at the South Transept
Turrets at the South Transept
Repair Implementation

Apse Buttress Elevations

114'-4"  4'-6"

53 54
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

- gravity
- wind
- thrust from wall
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 x μu
- Stability concern diminishes where center of mass is lower
Repair Implementation

Strengthening

Diagram showing repair implementation with annotations.

Strengthening - Pinnacles

Diagram showing strengthening details for pinnacles with annotations.
Repair Implementation

Strengthening – Upper Flyer

See detail, Item A.6.2.

Provide flat surface for alternative coping location, terminate reinforcing at intersect ofLost and Repair pry and reuse after completion ofcopings and grouting.

Provide access port into side of flyer to allow nailing to install, grout or release air, as necessary.

Temporary V-deal core hole and install an air relief port. Fill exterior face of core hole withney square or round dutchman repair.

TYPICAL UPPER FLYER

1/8" MIN, OR 1/2" DEPTH, WHICHEVER IS GREATER.

Repair Implementation

Strengthening – Lower Flyer

See detail, Item A.8.2.

Provide access port into side of flyer to allow nailing, grouting or release air, as necessary.

Temporary V deal core hole and install an air relief port. Fill exterior face of core hole withney square or round dutchman repair.

TYPICAL LOWER FLYER

1/8" MIN, OR 1/2" DEPTH, WHICHEVER IS GREATER.
So now you’ve designed something..

Center Coring
Center Coring

Center Coring

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## Center Coring

**Physical Property Requirements**

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

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## 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

“Unforeseen conditions”
Stone Restoration

“Unforeseen conditions”

Dismantling a Cathedral
Dismantling a Cathedral

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Dismantling a Cathedral

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Access

- Social distancing
- Reduced crew size
- Required face coverings

COVID-19

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

QUESTIONS?
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Seismic Assessment and Interventions for Historic Buildings – An Exemplary Case Study

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In the US, far more damage has been done to heritage structures and materials *in the name of earthquake safety* than has been caused by earthquakes

- Via “wrecking ball”
- Via insensitive, poorly conceived seismic strengthening projects
New and Non-Heritage Structures

Technical Considerations

Seismic safety  Cost ($)

Heritage Structures

Technical Considerations

Seismic safety  Cost ($)

Cultural Considerations

“Cost”
Typical Priorities on Heritage Projects

Safety

Economy

Preservation

Recommended Engineering Priorities on Heritage Projects

Engineering for Seismic Safety

Engineering for Preservation

One goal for this webinar is to illustrate why these seemingly “competing” approaches are complementary, not mutually exclusive, and to illustrate how they were successfully incorporated into a real-life project.
Earthquakes and Unreinforced Masonry

Earthquakes and Unreinforced Masonry
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Earthquakes and Unreinforced Masonry

www.ceaps.umn.edu
Earthquakes and Unreinforced Masonry

Earthquakes and Unreinforced Masonry
Sherith Israel – The Basics

- 1904/5 unreinforced brick masonry bearing wall building with interior steel framing and Colusa Sandstone veneer
- Engineer/Architect: Albert Pissis
- Mural painted interiors by Attilio Moretti
- Opalescent stained-glass windows by Emilio Pissis
Interior partitions and ceilings:
- wood framed
- wood lath and mural painted plaster

Main dome
Drum floor level
"Moses" window
Balcony level
Sanctuary level (2nd floor)

Wood diaphragms at roof (open), balcony (open), sanctuary and entry levels

Plan-articulated exterior masonry walls
- 120 feet: street to top of dome
- 100 feet: sanctuary floor to top of dome
- 65-75 feet: street to main roof

Steel-framed dome (sheet metal clad to simulate masonry)

Supporting steel trusses and columns

Tension-only braced round drum truss

Base Image: ELS Architecture

8 “positive connections” between steel framing and perimeter masonry per story

“Positive connection” to masonry, (8)
Areas of Significance

"Very significant" areas

- Off-limits for other reasons

- Sanctuary
- Sanctuary lobby
- Balcony Level
- Sanctuary Floor Level

Balcony level
Benchmarking

Using prior loading events to assist in understanding how the structure behaves when loaded

- Requires understanding of the damage that resulted from prior loading
  - Documentary evidence
  - Physical evidence
- Requires estimating prior loading intensity
  - Prior loading > future loading?
  - Future loading >> prior loading?
- Entails calibrating / validation structural models to correctly predict prior damage
  - Avoid the pitfalls of performing an a priori analysis when there is no analytical precedent
  - Use for live load & wind load, as well as seismic

Old Lane Hospital never re-occupied after earthquake
A time capsule, 1906 earthquake damage was present throughout the Gable end wall.

"Positive connection" point
A time capsule, 1906 earthquake damage was present throughout.
Top of tension-only braced "drum truss"

ShakeMap for 1906 Scenario event
Intensity maps are an indirect measure of seismic shaking: the contours are of observed damage:
- shaking intensity
- competence of the building inventory
A Brief Digression

Engineering for Seismic Safety

Engineering for Preservation

A Brief Digression

Engineering for Seismic Safety

Engineering for Preservation

Capitalize on Inherent Strengths

Resolve Critical Vulnerabilities
Capitalizing on inherent strengths

- recognize that the structure must have inherent strengths
  - It doesn’t matter that the structure isn’t code compliant
  - Don’t let “stigma” affect your engineering
- identify, quantify and leverage inherent strengths
  - Minimizes interventions, which minimizes disruption/costs
- the entire project team must be willing to fully embrace non-compliant inherent strengths
  - Design professionals, developer, jurisdiction

Resolving the critical vulnerabilities

- recognize that noncompliance with Code ≠ critical vulnerability
- identify and prioritize the vulnerabilities
  - Target and correct the most critical ones
- surgically target the highest priority vulnerabilities, explicitly considering means of access for construction
  - Remember that Disruption = Deficit
  - Pursue elegance, not brute force
Pearl #1

Don’t destroy the reason for saving the building in the course of saving the building

Pearl #2

Seek to preserve historic structure as well as the finishes

- Don’t relegate the historic structure to “the museum”
- Preservation isn’t about just saving the pretty stuff
Pearl #3

Supplement the inherent strengths, don’t supplant them

Pearl #4

Don’t try to force an old building to behave like a new one
Pearl #5

Don’t use a new building code on an old building

Pearl #6

If you can resolve 80% of the risk for 20% of the costs, why wouldn’t you?
Pearl #7

It’s not just about the elegance of your design, it’s about access for construction

Applications to Sherith Israel
Inherent strength
The arch has been around for thousand of years

We usually conceive of arches as 2-D elements, but masonry arches can provide stability in a 3-D space as well
Can these walls support themselves out-of-plane?

Out-of-plane Pushover Analyses
- Confirmed and quantified out-of-plane wall characteristics
- Identified hot spots

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Another Inherent Strength

- We often think of flexible (wood with large openings) diaphragms as something that needs to be corrected.
- Upon close examination, however, the diaphragms proved to be an inherent strength because they de-couple response of the in-plane and out-of-plane walls
The exterior masonry walls account for more than 80% of the seismic mass in Sherith Israel...

- Light walls
- Heavy, rigid floors

versus

- Heavy walls
- Light, flexible floors

Buildings with rigid diaphragms:

- In-plane shear: All the mass acts together at the plateau (maximum) acceleration, so the walls in each direction must resist 100% of active seismic mass
- Out-of-plane: Floor-to-wall ties in each direction must resist wall seismic mass acting at plateau acceleration
Buildings with flexible diaphragms:

- **In-plane shear:** Walls must resist self-mass at plateau acceleration + balance at reduced acceleration.
- **Out-of-plane:** Floor-to-wall ties in each direction can be designed for a reduced acceleration.

A building with flexible diaphragms like Sherith Israel will have lower in-plane shear demands on their walls and lower out-of-plane demands on their floor-to-wall ties than an equivalent building with rigid floor diaphragms.

*So why would you want to transform its flexible diaphragms into rigid ones?*
The two prior engineering solutions involved installing either rigid concrete and metal deck diaphragms, or massive steel horizontal trusses, to create rigid diaphragms. Both called for shotcreting the masonry walls to strengthen them.
Seismic Interventions at Sherith Israel

The “go around it” school of seismic intervention

Seismic Interventions

- Solutions that preserved both the interior and exterior historic fabric were developed
  - Employed “first principles” approach to supplement inherent strengths
  - Super-elastic nitinol tension ties added strategically to enhance gable end wall performance
  - Vertical and horizontal center cores with engineered polymer grout
  - Compression-only “Rocking block” pilasters
  - CFRP “catenary” to stabilize planar exterior masonry wall area
  - Various traditional measures
  - No disruption to historically sensitive finishes
  - No expensive base-isolation or damping systems
  - No global foundation strengthening
Center Cores

Brick masonry walls

- Due to “decoupling,” the shear resistance of the brick masonry walls did not require enhancing, thus the interior and exterior finishes on the exterior walls were left intact.
- Center cores were used to improve the integrity of the masonry and to address high local h/t concerns.
Center cores

- Center cores consist of holes cored in masonry into which reinforcing steel is installed and grouted into place
- Center coring is a technique adapted from the drilling/mining industry
- Center cores can boost the in-plane shear strength, out-of-plane flexural strength, in-plane and out-of-plane post-elastic stiffness, and toughness of the masonry
  - In some jurisdictions, it is not permitted to be used to supplement masonry shear strength
- We used it as “integrity steel” and to rectify h/t concerns

Why Integrity Steel?

- Intercepting potential crack planes is an effective way to slow down the disintegration of masonry under cyclic loading
- center cores
- r/c bond beam
- CFRP wrap

- Over 8,000 lineal feet of cores
- Typical core heights ranged from 60 to 75 feet
- Vertical center cores terminate in r/c bond beam
- Horizontal center cores integrate orthogonal walls

Center cores installed from roof

Interior side of Colusa sandstone coping demolished and replaced with r/c

Center core drill rig
Center core customization

- Center core projects commonly use wet-cored 6" diameter holes and cementitious grouts
- In Sherith Israel, we used dry-cored holes (3-inch and 4-inch dia.) and polyester resin-based grout

Advantages of polyester resin-based grouts (PRBG)
- PRBG is not water-based and does not have as great a potential to damage historic finishes if it bleeds out of the wall
- PRBG typically has much higher tensile, compressive and bond strengths than cementitious grout
- PRBG has much lower modulus than cementitious grout, with a flexibility that is much close to lime mortared brick masonry
- No concerns regarding bond due to effects of porous masonry
- PRBG provides protection against corrosion via encapsulation rather than passivation
Center core customization

- We developed a custom grout mix in our laboratory to optimize cost and performance
  - modulus of elasticity - compatibility
  - flow
  - Bleed/permeation
  - cracking during cure

Potential disadvantages of polyester resin-based grouts

- By volume, PRBG is typically more expensive than cementitious grout but grout volumes can be kept smaller
- PRBG exudes a strong odor which may limit the conditions under which they can be used
- PRBG may develop high bleed, exothermic, resin-rich lenses that are prone to cracking during cure
- PRBG is difficult to pump if mix is optimized, but can be installed without pumping in most circumstances
- Mix design must address high shrinkage of pure resin
Center core precautions

- Assess condition of masonry and sensitivity of finishes to determine method of coring and filling of cores
- Conduct ample laboratory testing to develop appropriate grout mix design for extant conditions
- **Conduct mock-ups** to ensure grouting methodology will work
- Conduct regular and appropriate testing of materials/mix on-site
- **Conduct destructive testing** after installation to confirm adequacy of installation
Nitinol Tension Ties

15th-Century tie beams in St. Mary’s Church, England

Used for many reasons:
• Overall structural stability
• Outward thrust due to roof weight
• Ratcheting associated with soil movement
• Resisting wind/seismic forces

Medieval iron chain tie rods in Westminster Abbey

1en.wikipedia.org/wiki/Tie_(engineering)
2abelard.org/France/using-metal-in-cathedral-construction.php
Iron tension tie retrofit at base of arch

Steel tension ring retrofit around base of dome

Steel tension tie retrofit through center of dome

- Update the concept
  - Avoid disruption to the sanctuary
  - Neutralize the disadvantages of using iron or steel


Base Image ELS Architecture

- **Steel octagon tension “ring”** (2-inch diameter Dywidag rods) with steel plate hubs
- **Nitinol “harp”**

**Design goals**
- promote re-centering of gable end walls
- resist out-of-phase outward behavior of opposing walls
- improve global wall stability
- “cinch” roof diaphragm to exterior walls
Nitinol “harp” anchored to interior bond beam (attic interior)

Parapet bond beam

Challenge to find a physical location in planar space that would work from a structural standpoint
Substituting Nitinol for iron / steel

- What is Nitinol?
  - Nickel Titanium – Naval Ordinance Laboratory
  - Super-elastic alloy of nickel and titanium
  - Most commonly used in medical applications
  - Shape memory (heat activated)
  - Elastic limit around 5%
  - Ultimate strain of about 14%
  - Extremely hard and difficult to machine

![Before, During, After images of Nitinol and Steel comparison](image)

![Stress vs. Strain graph comparing Nitinol and Steel](image)
Testing Program:
- Conducted testing to verify properties of the wire and the performance of the anchors.
- Tested at three different temperatures covering likely range of temperature in the attic.
- Cycles the wire to 2, 4, 6, and 8 percent, and then to failure.

Tune System Response:
- Force: Quantity / diameter of nitinol wires
- Displacement: Overall gage length of wires
Constructability

- Design for Constructability
  - NO HOT WORK
  - No Shoring
- Design for Constructability
  - Each component light enough and short enough to be carried by two workers into and around attic space

Compression-Only “Rocking Block” Pilasters
The Problem (1)

North wall is planar (i.e. not plan-articulated)...

...but is supported out-of-plane by four lath & plaster partitions.

The Problem (2)

Stair openings at balcony level essentially preclude diaphragm participation

- The need to improve the out-of-plane stability of the north wall required either a tough choice, either...
  - Improve the lath and plaster partitions, or
  - Install new “props” on the exterior.
The Solution

Compression-only “Rocking block” Pilasters, typ.

- The pilasters were designed to limit northward movement of the wall (and prevent unrestrained outfall), but to permit southward movement.
- Compression-only "Rocking block"
- Neoprene bearing pads
- Sleeved dowels

Rocking-Block Pilasters
- Resist outfall of north wall
- Simulate plan articulations of other walls
- Permit uplift and rotation
- Permit differential displacement along north wall
Areas of Significance

- Sanctuary Floor Level
- Off-limits for other reasons

Sanctuary lobby

Balcony Level

“Very significant” areas

Rocking block pilasters

CFRP catenary under Colusa sandstone

High h/t
More Traditional Interventions
Reinforced concrete bond beam

- Design goals
  - To provide restraint against crack growth and out-of-plane displacement across cracks at the “free edge” of the masonry at the roof
  - To provide anchorage for the vertical center cores
  - To help stabilize the gable end walls and provide anchorage for the nitinol tension ties
Earthquakes and Unreinforced Masonry
Floor-to-wall ties

- Designed to integrate floor/roof diaphragms and masonry walls
- Explicit consideration of access for installation
- Conducted testing to justify modified installation procedures and achieve desired performance
Floor-to-wall ties installed within balcony rake
Areas of Significance

"Very significant" areas

Off-limits for other reasons

Storage rooms

Sanctuary

Sanctuary lobby

Balcony Level

Sanctuary Floor Level

Thank you!

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