WJE ENGINEERS ARCHITECTS MATERIALS SCIENTISTS

Repairing Earthquake Damage at The Washington National Cathedral

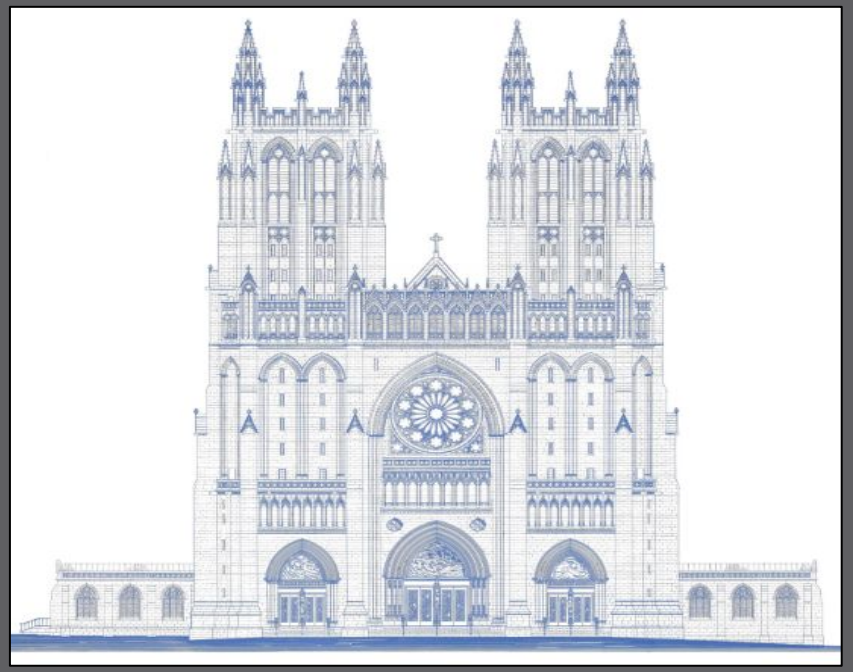
Kelsey E. Sheridan, PE

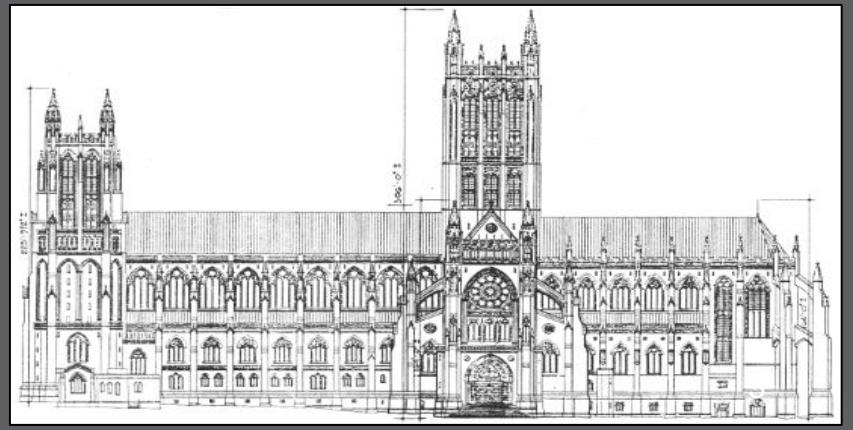
Washington National Cathedral

Overall Length:	517ft
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…



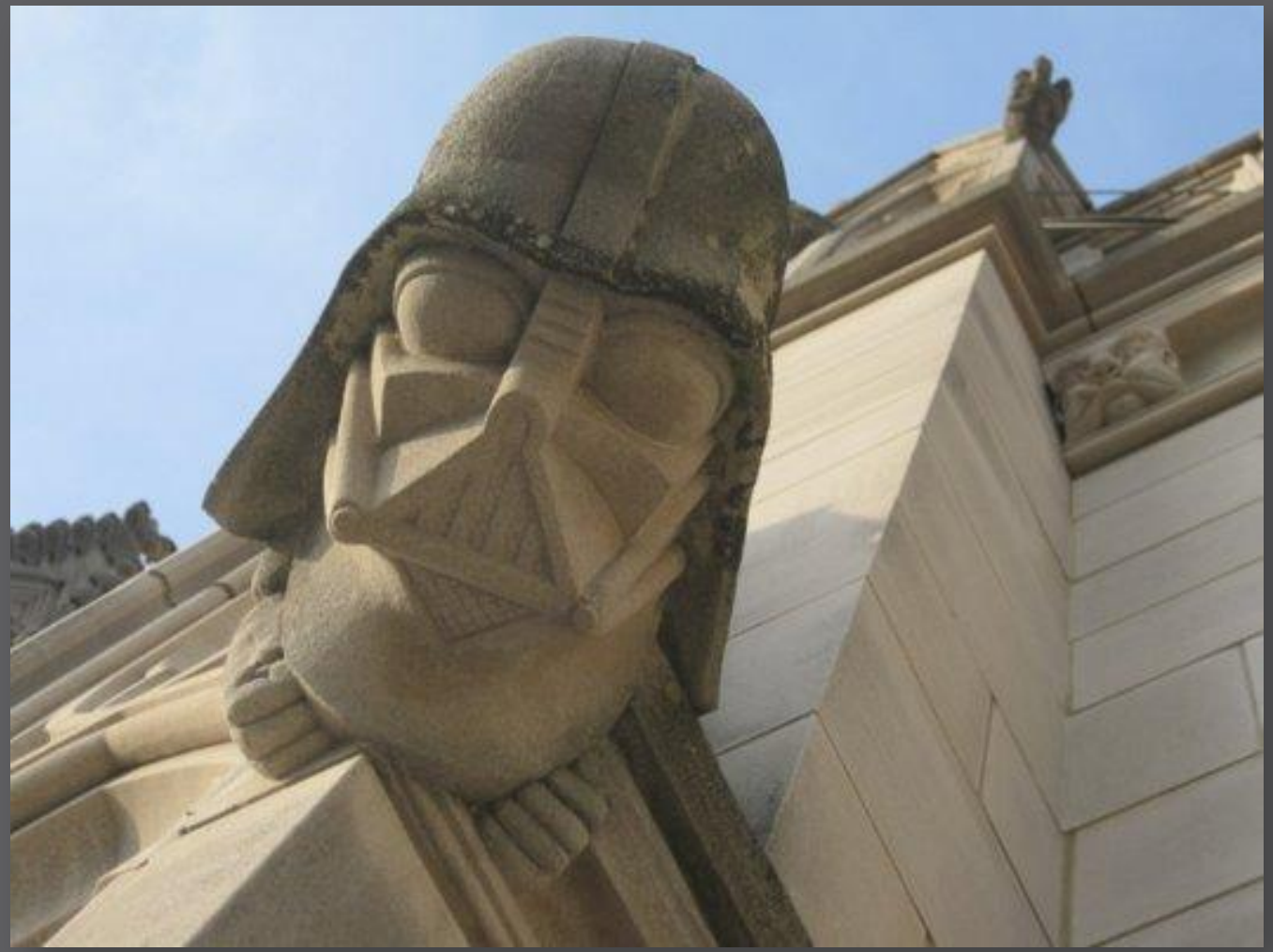


Washington National Cathedral

Gargoyles!

and grotesques..

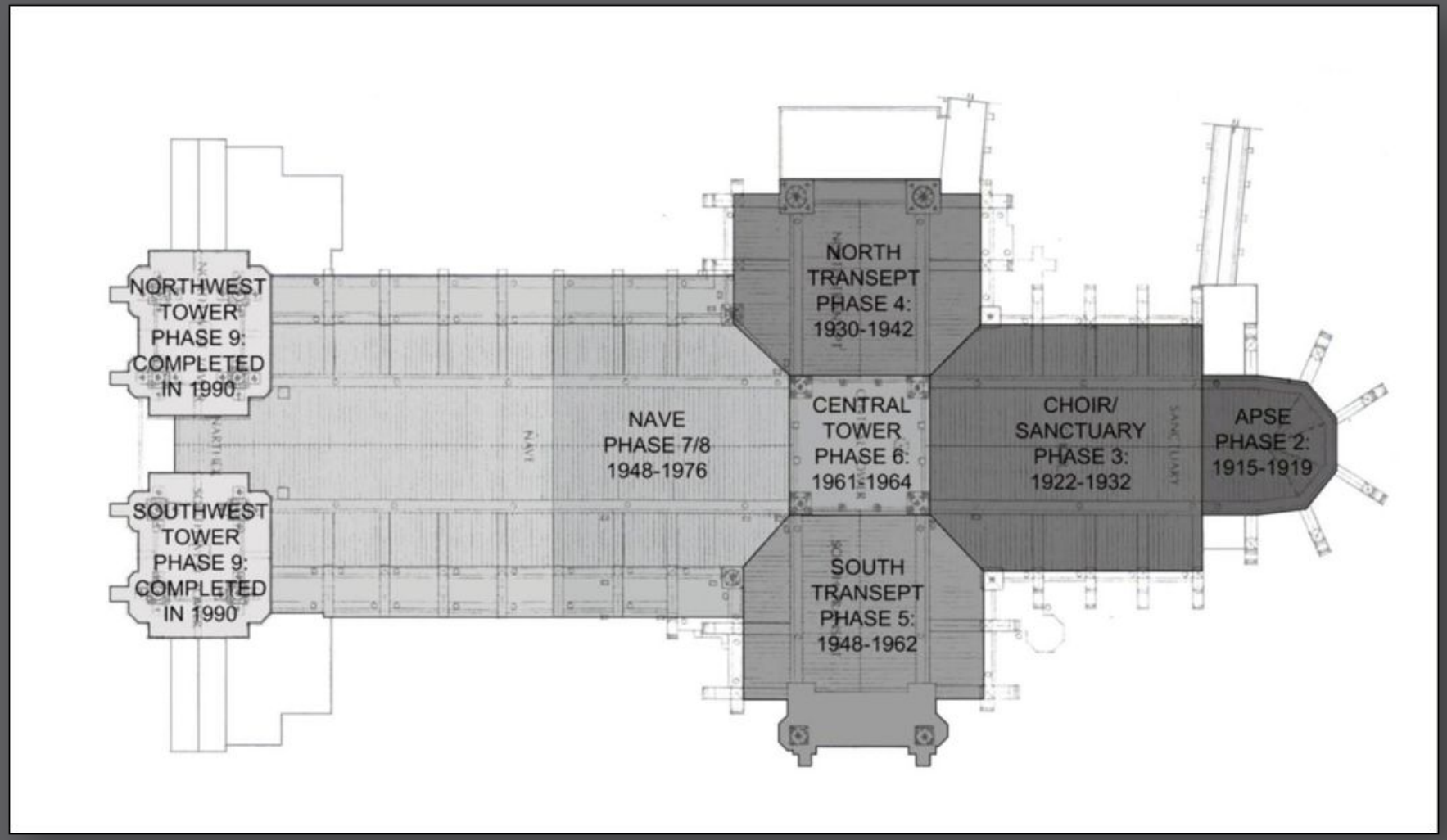
Washington National Cathedral



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

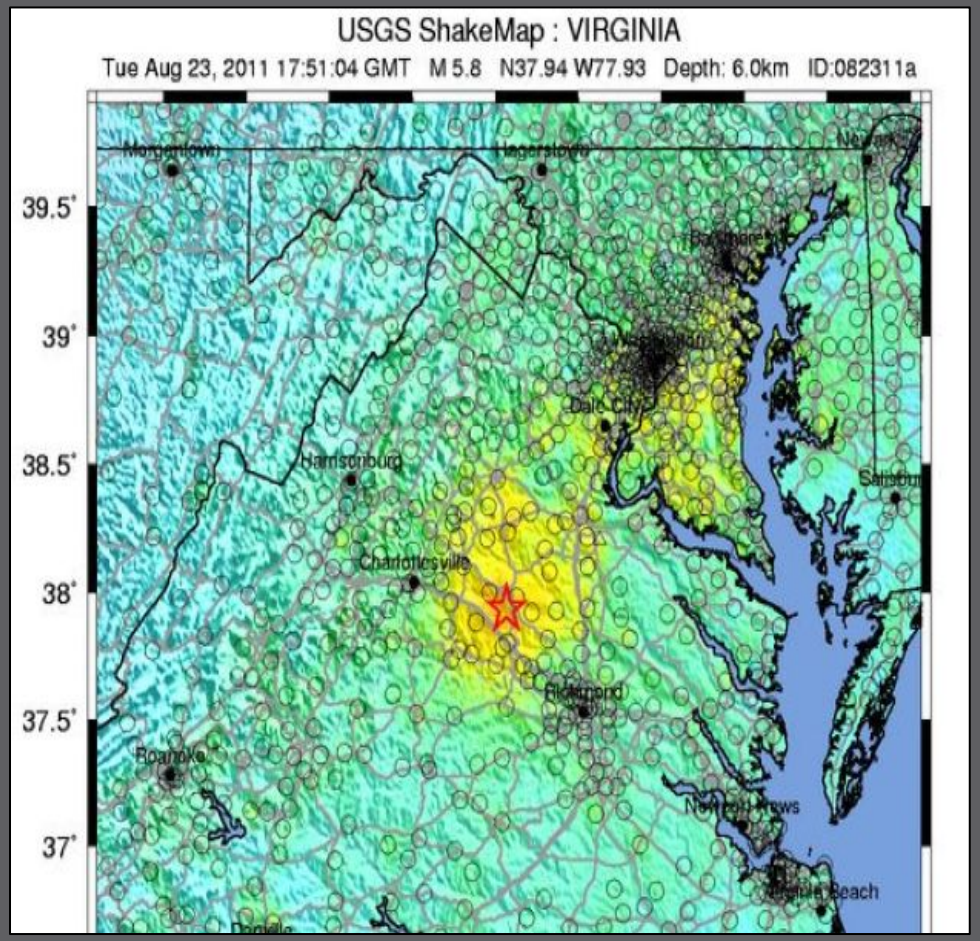
Condition

- 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 “Mineral” Event

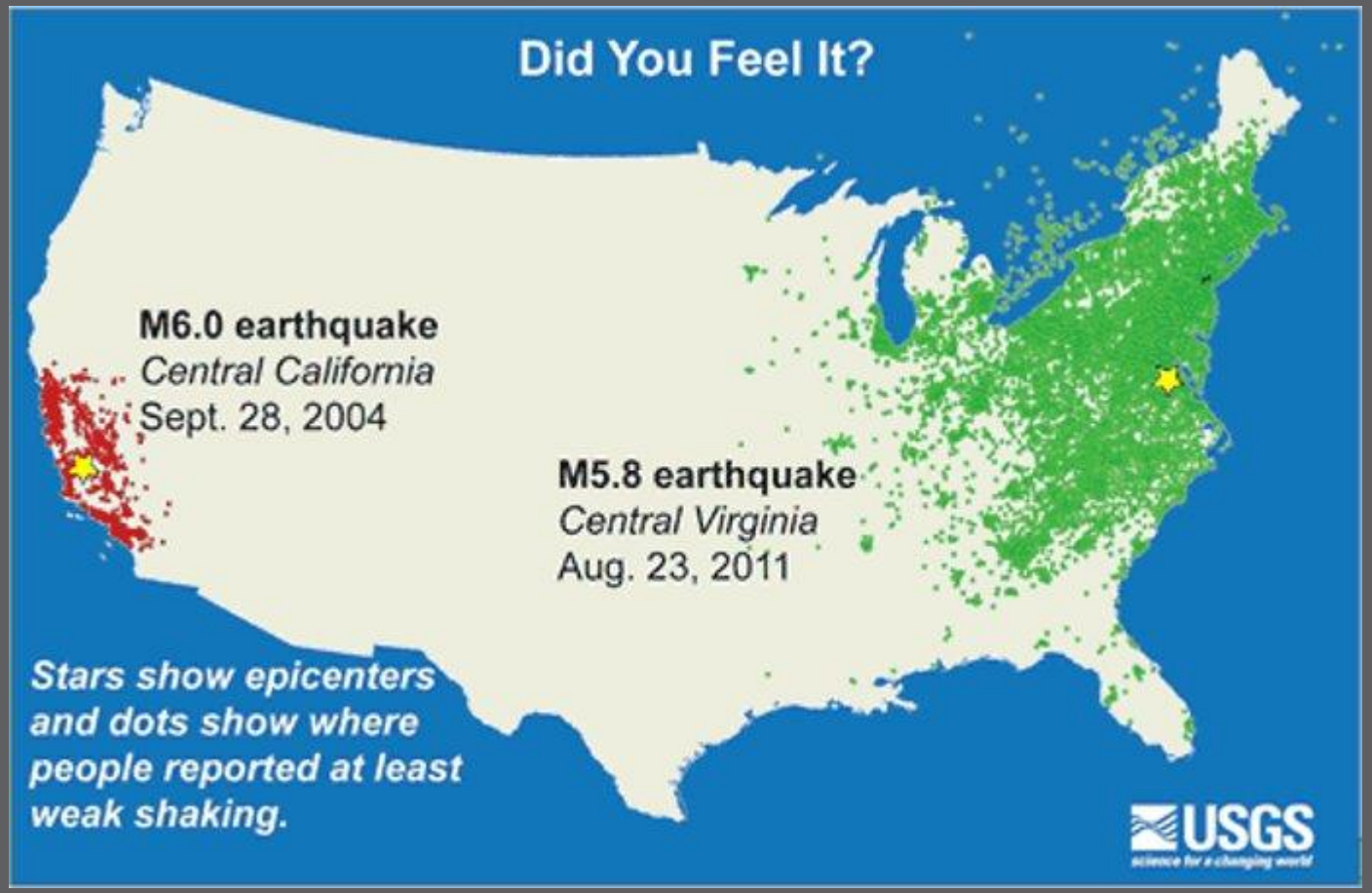
Date:	August 23, 2011
Time:	1:51 PM EDT
Magnitude:	5.8M*w*
Location:	Mineral, VA
Depth Below Surface:	3.7 mi
Distance From Washington DC:	84 mi

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



PERCEIVED SHAKING	Not felt	Weak	Light	Moderate	Strong	Very strong	Severe	Violent	Extreme
POTENTIAL DAMAGE	none	none	none	Very light	Light	Moderate	Moderate/Heavy	Heavy	Very Heavy
PEAK ACC.(%g)	<.17	.17-1.4	1.4-3.9	3.9-9.2	9.2-18	18-34	34-65	65-124	>124
PEAK VEL.(cm/s)	<0.1	0.1-1.1	1.1-3.4	3.4-8.1	8.1-16	16-31	31-60	60-116	>116
INSTRUMENTAL INTENSITY	I	II-III	IV	V	VI	VII	VIII	IX	X

The “Mineral” Event



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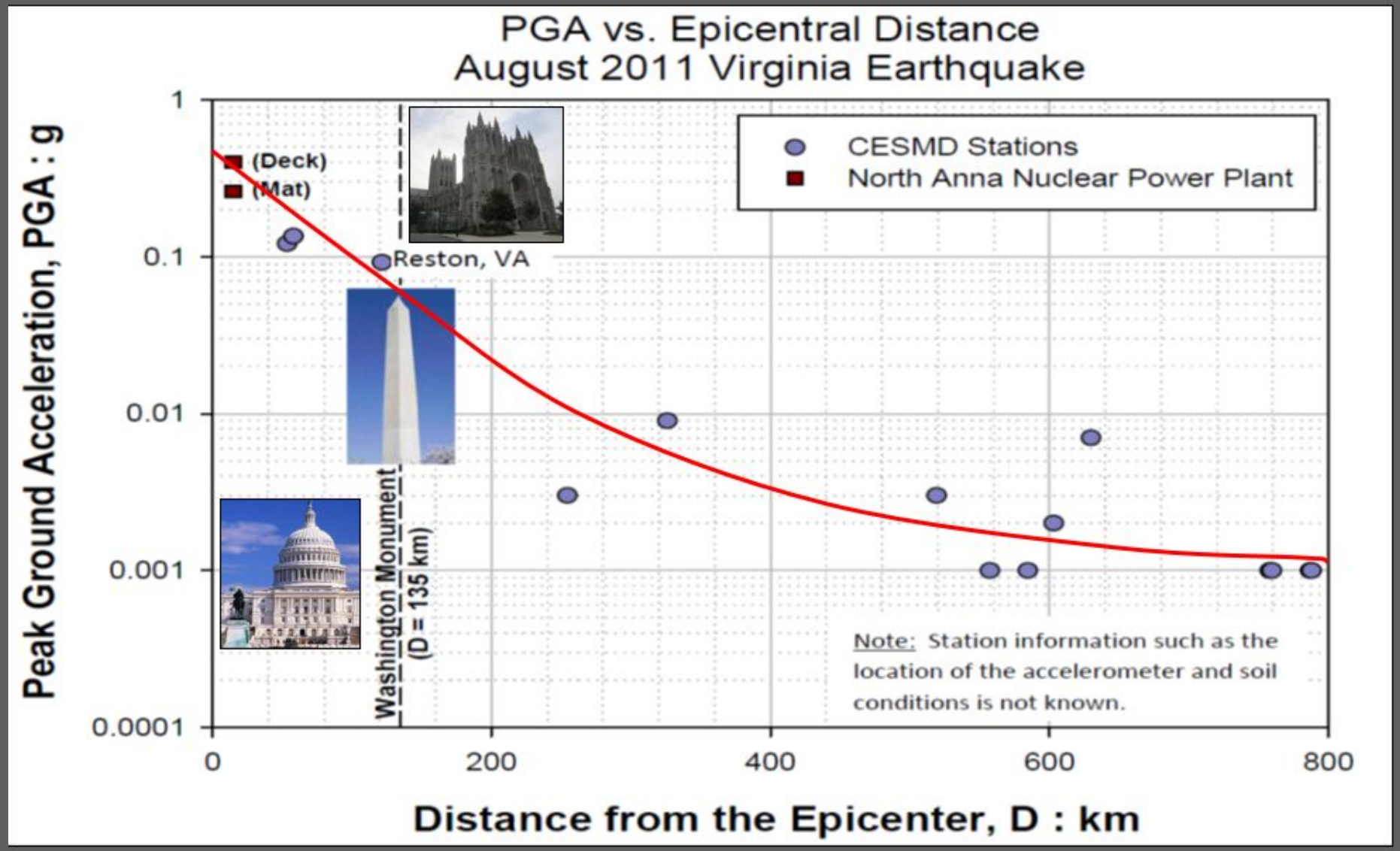


Critical Post-EQ Events & Activities

Make Safe Operations

Interior

- Debris Netting System

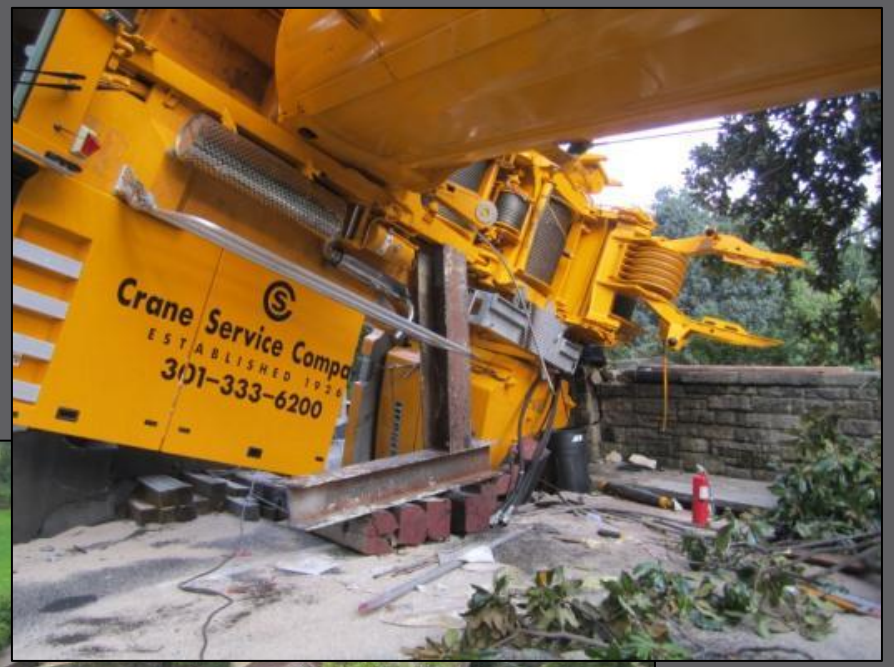
Exterior

- Chain Link Fence
- Roof Repairs
- Egress Protection

Critical Events & Activities

Crane Collapse/Investigation/Removal

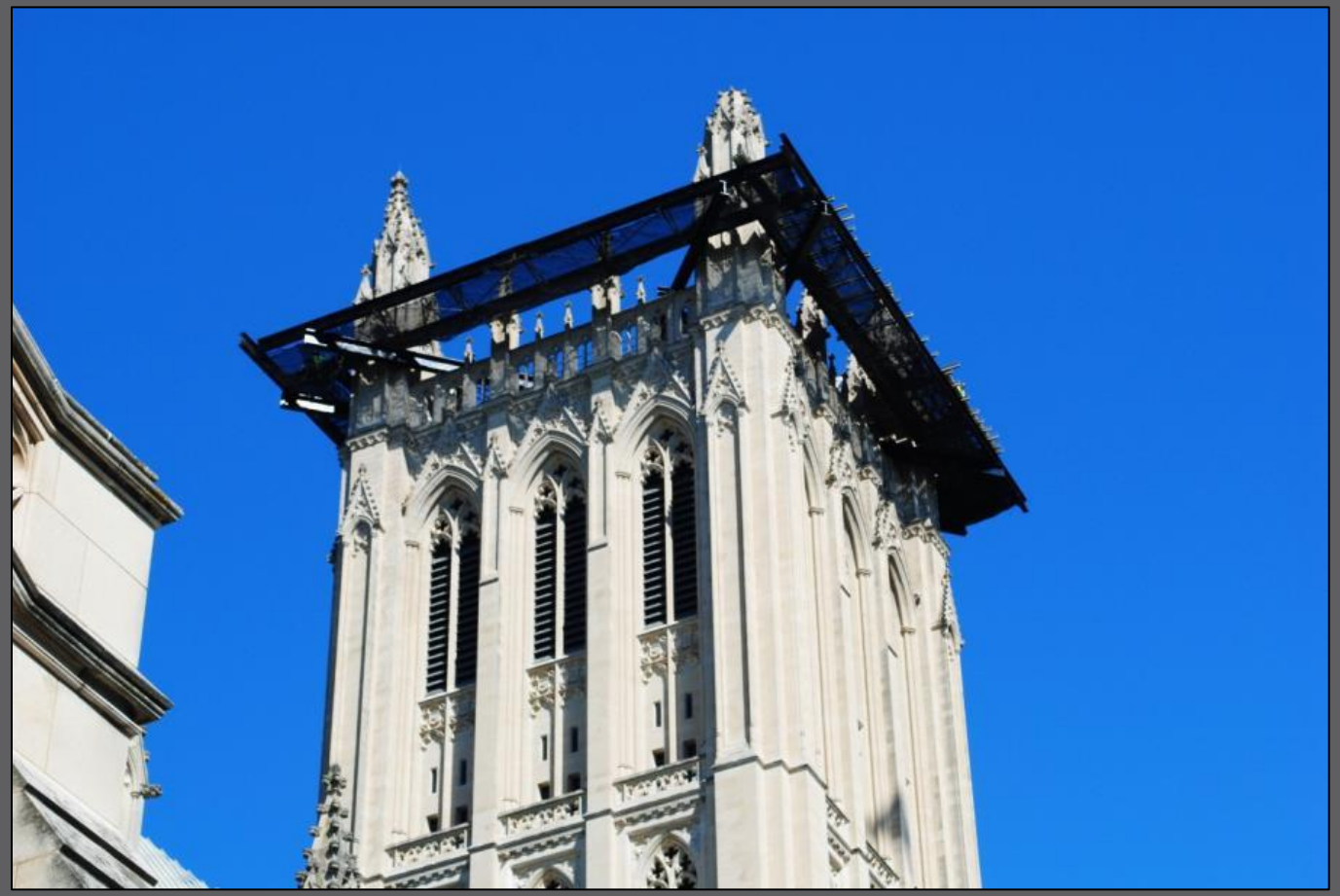
- September 7, 2011
- Liebherr LTM1400-7.1,400 Metric Ton Crane
- Damage to Herb Cottage
- 9/11 Services Cancelled



Critical Events & Activities

Central Tower Scaffolding of Grand Pinnacles

- Completion of Scaffolding and Protective Netting

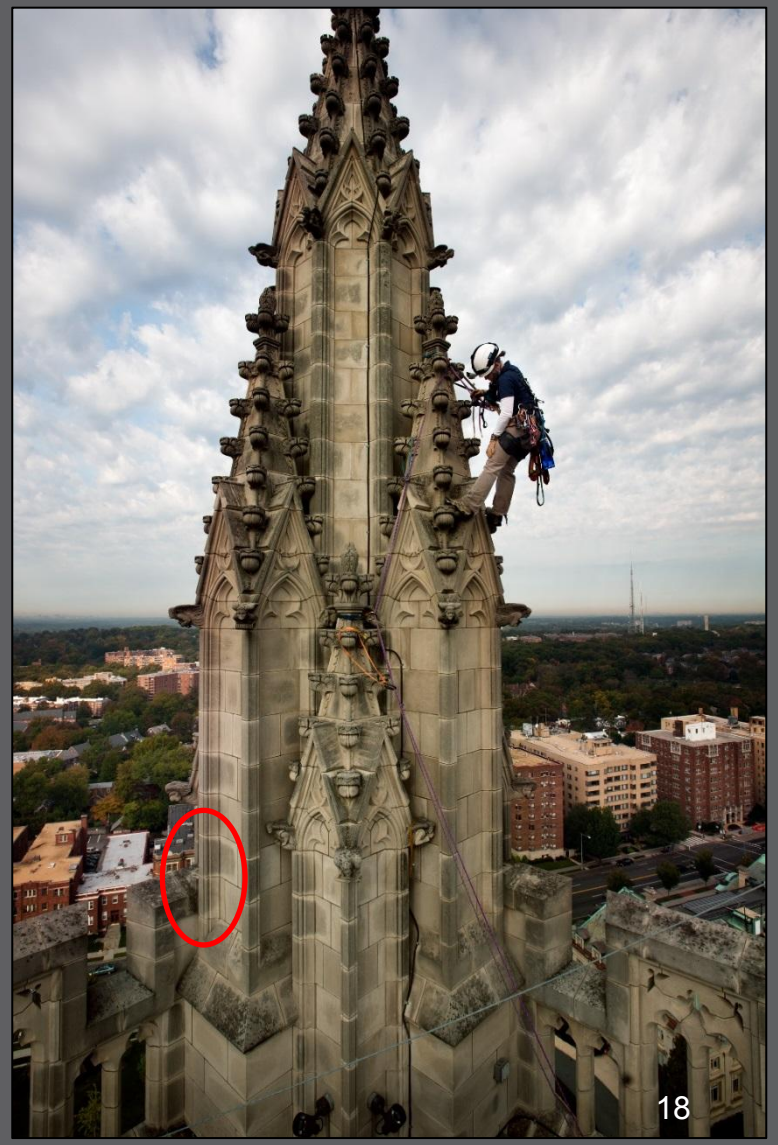


Critical Events & Activities

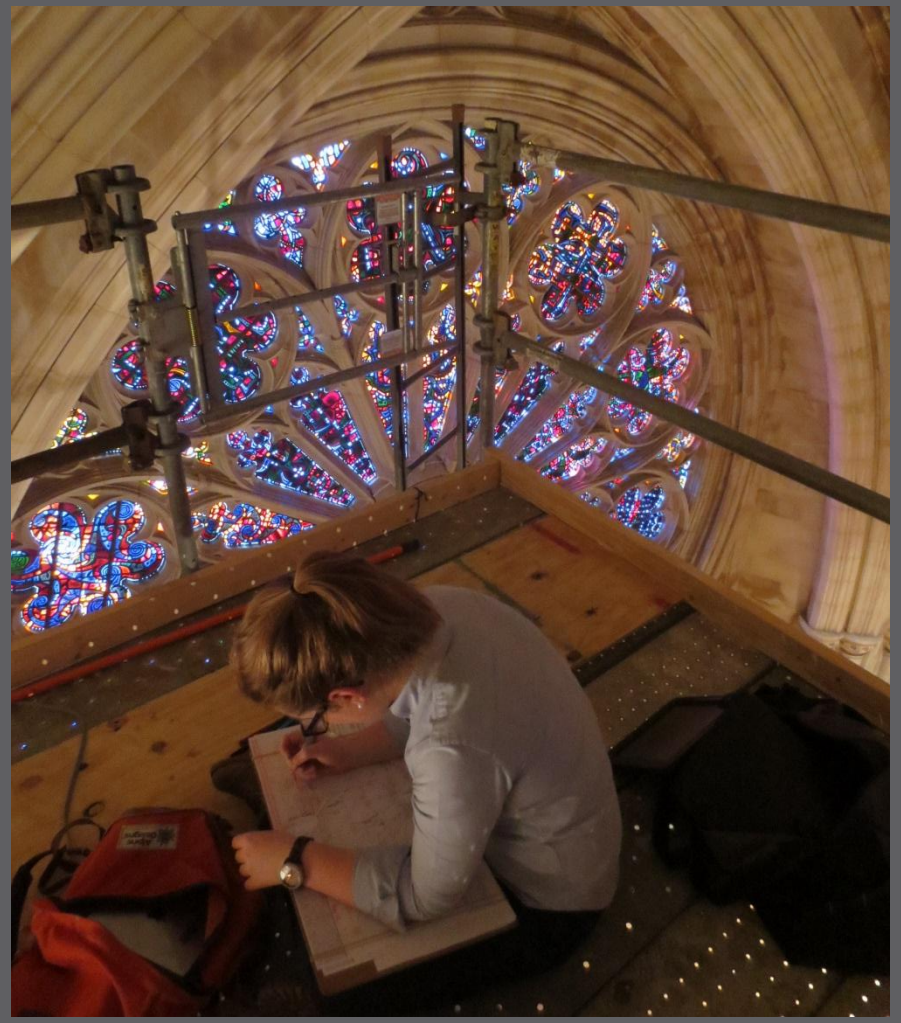
DAT Survey

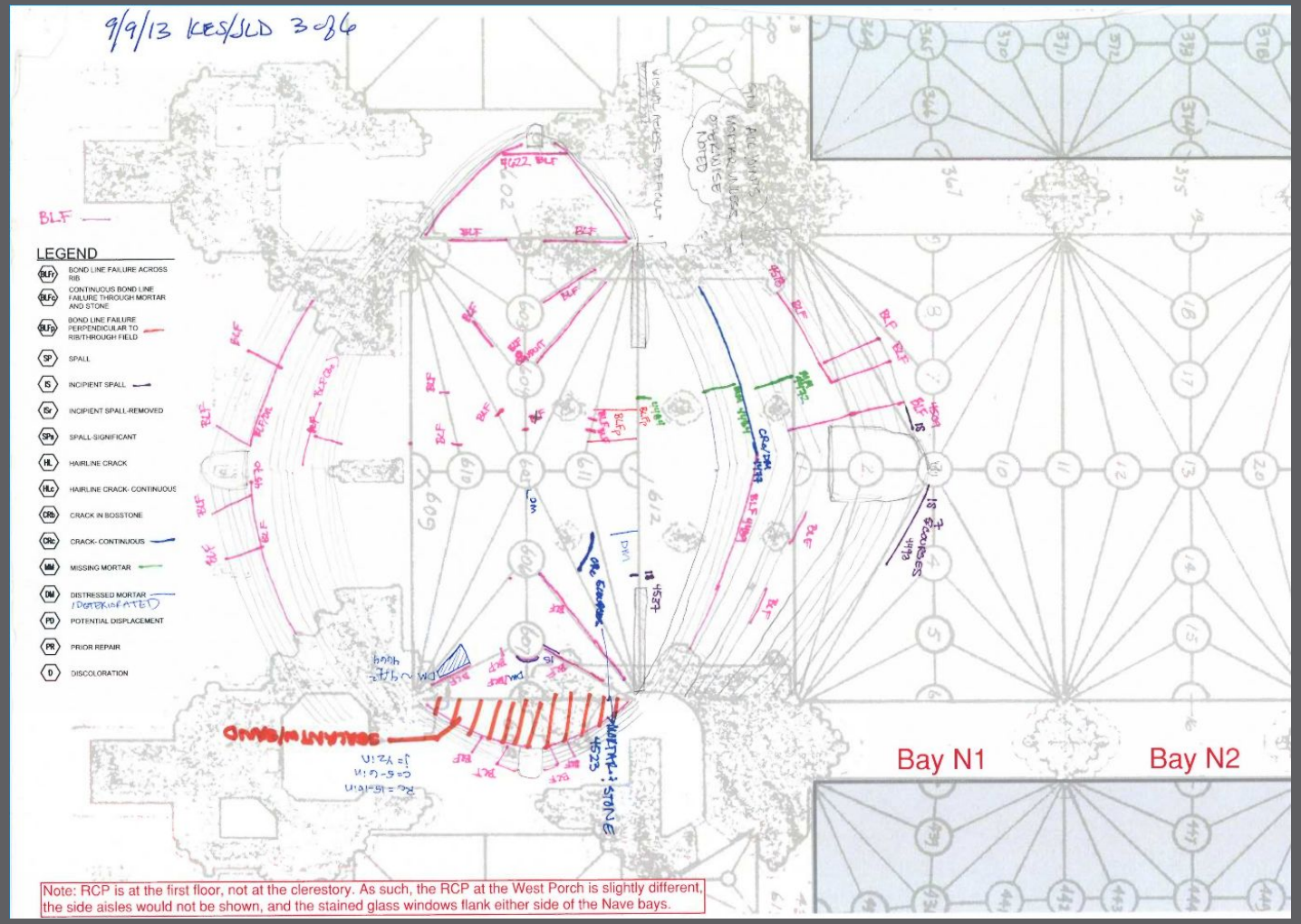
Critical Events & Activities

DAT Survey of Central and West Towers



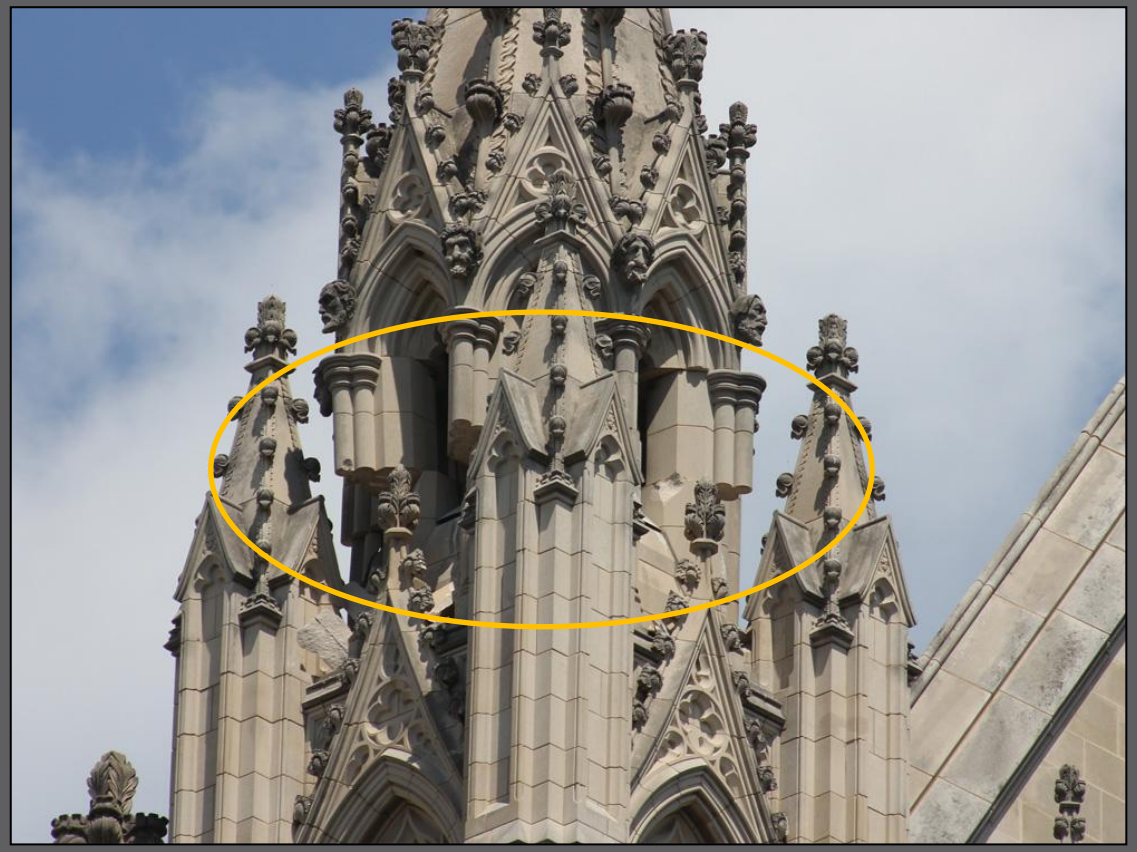
Survey/Documentation of Interior





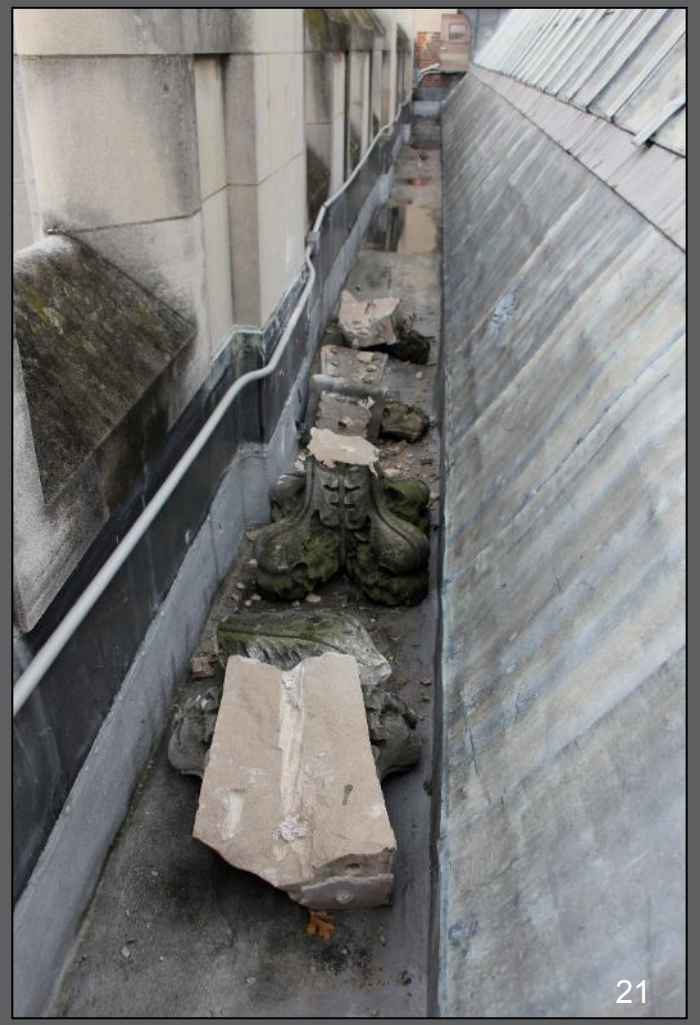
Survey/Documentation of Exterior

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



Seismic Damage

Pinnacles

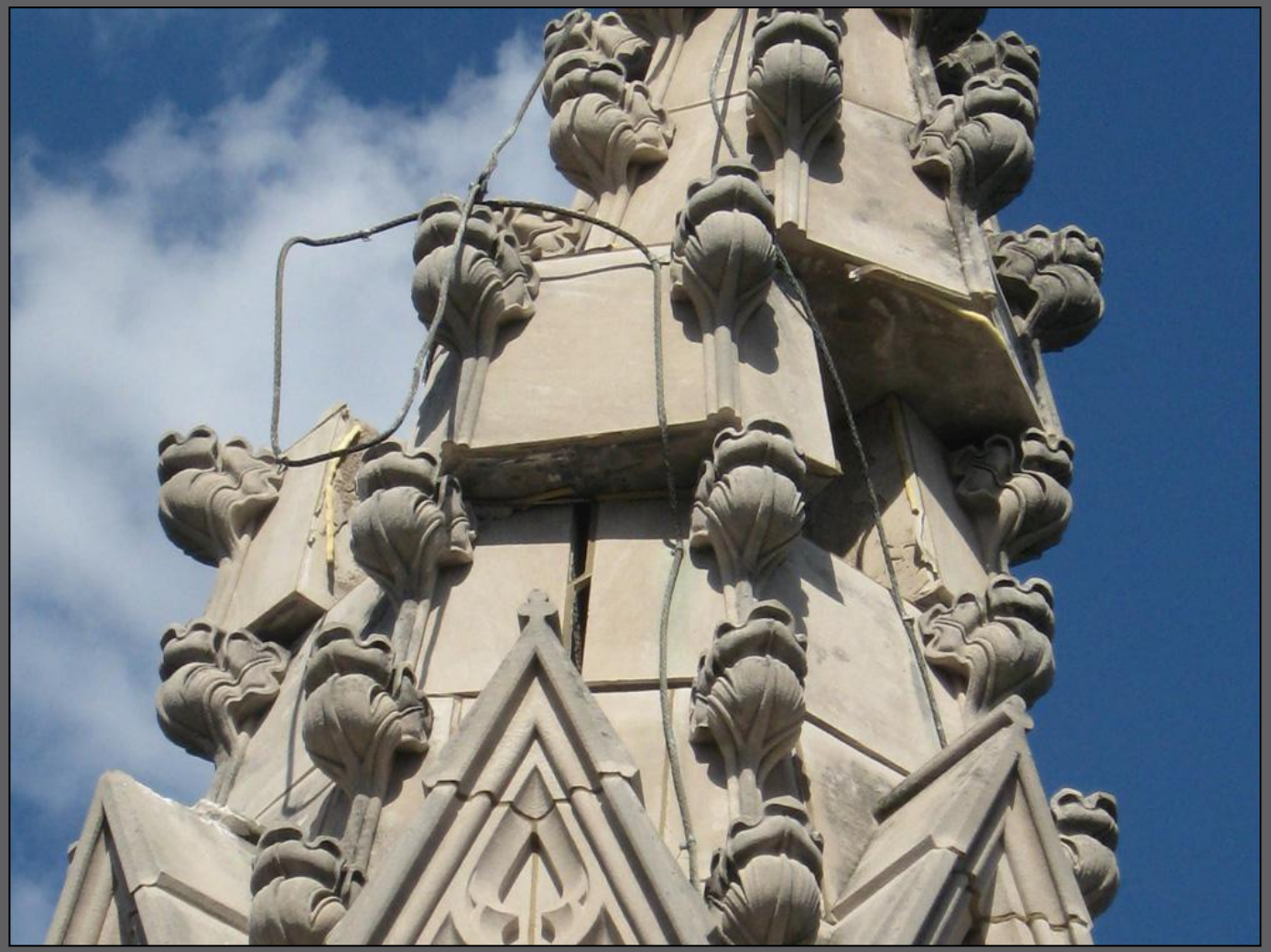


Seismic Damage

Pinnacles

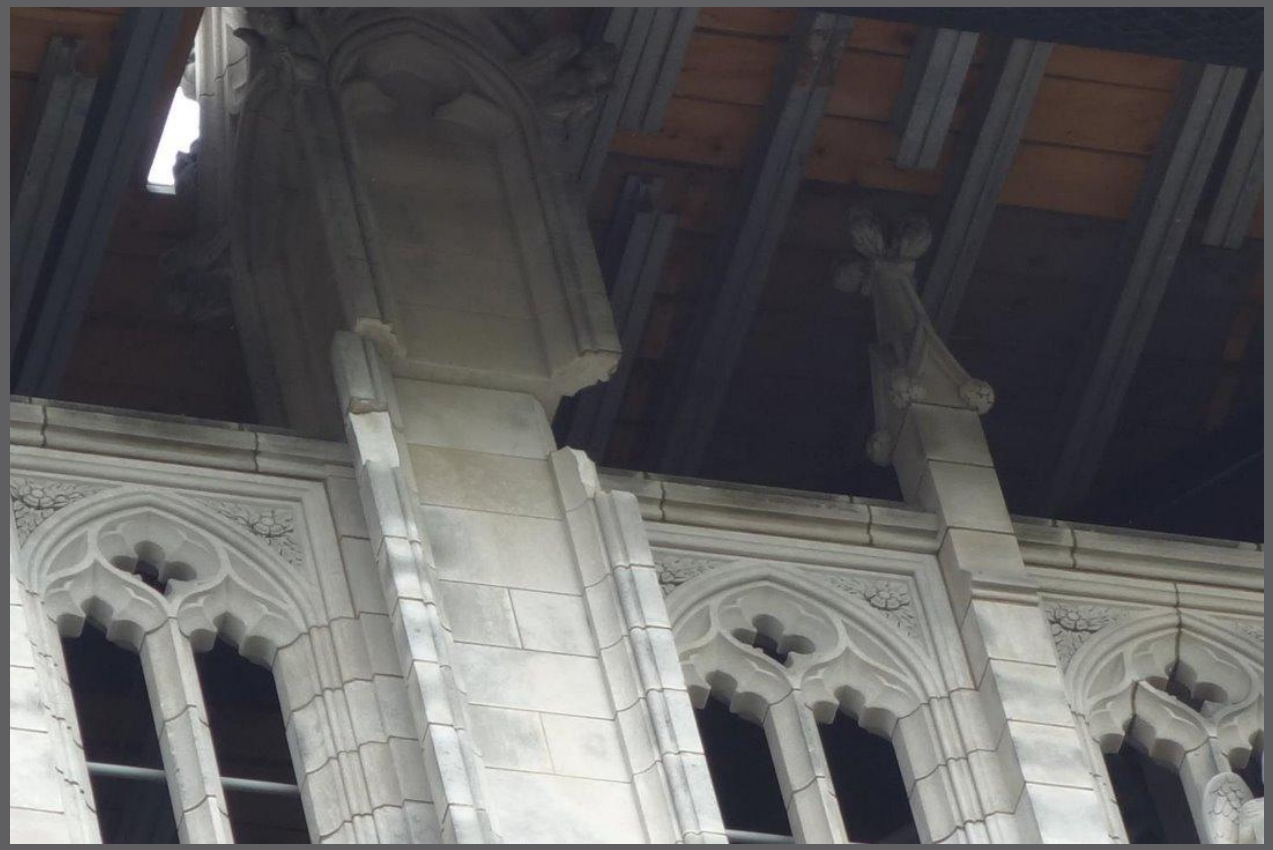
Seismic Damage

Pinnacles



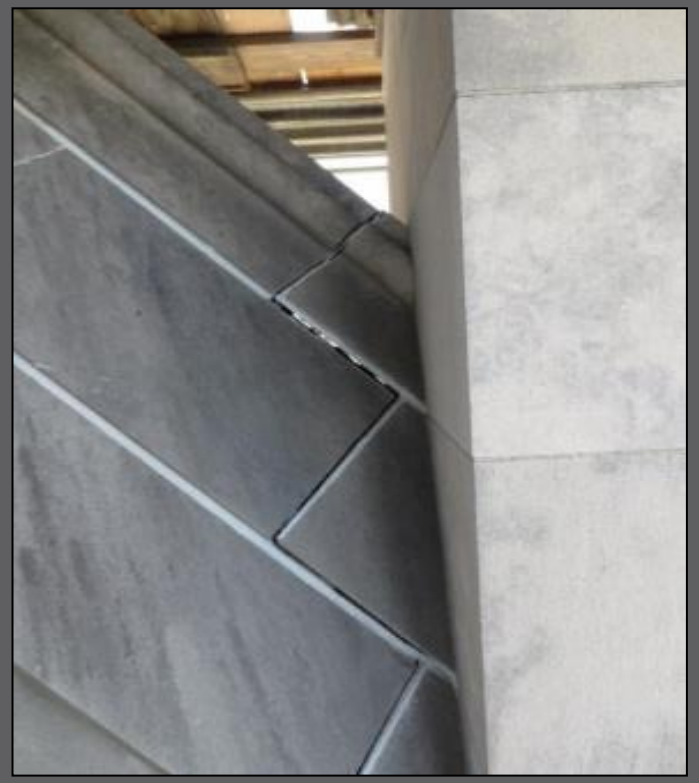
Seismic Damage

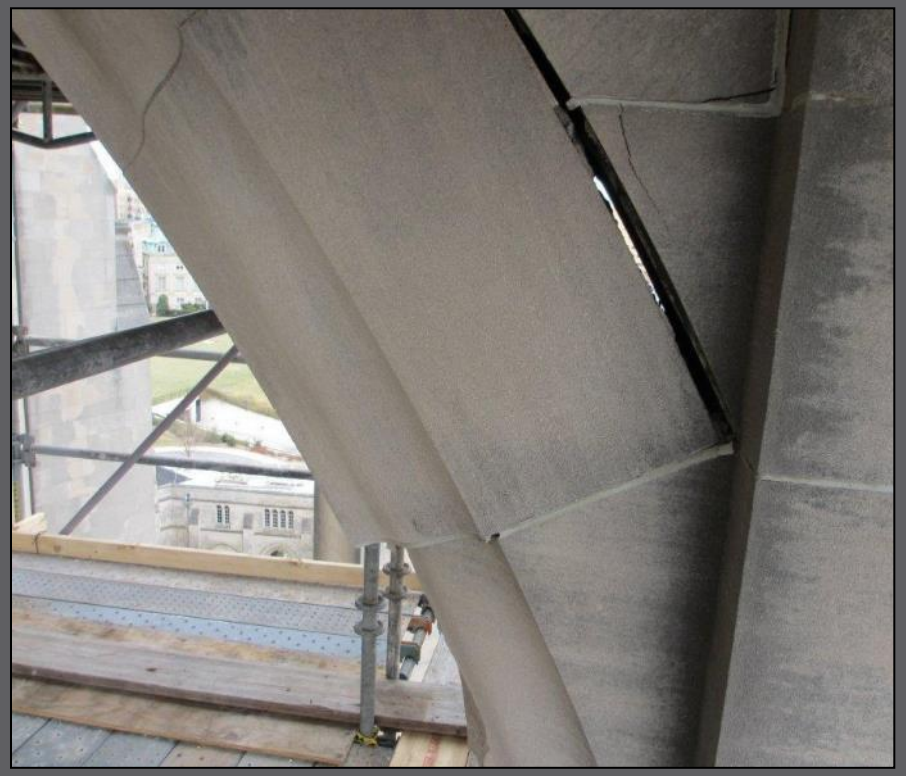
Pinnacles



Seismic Damage

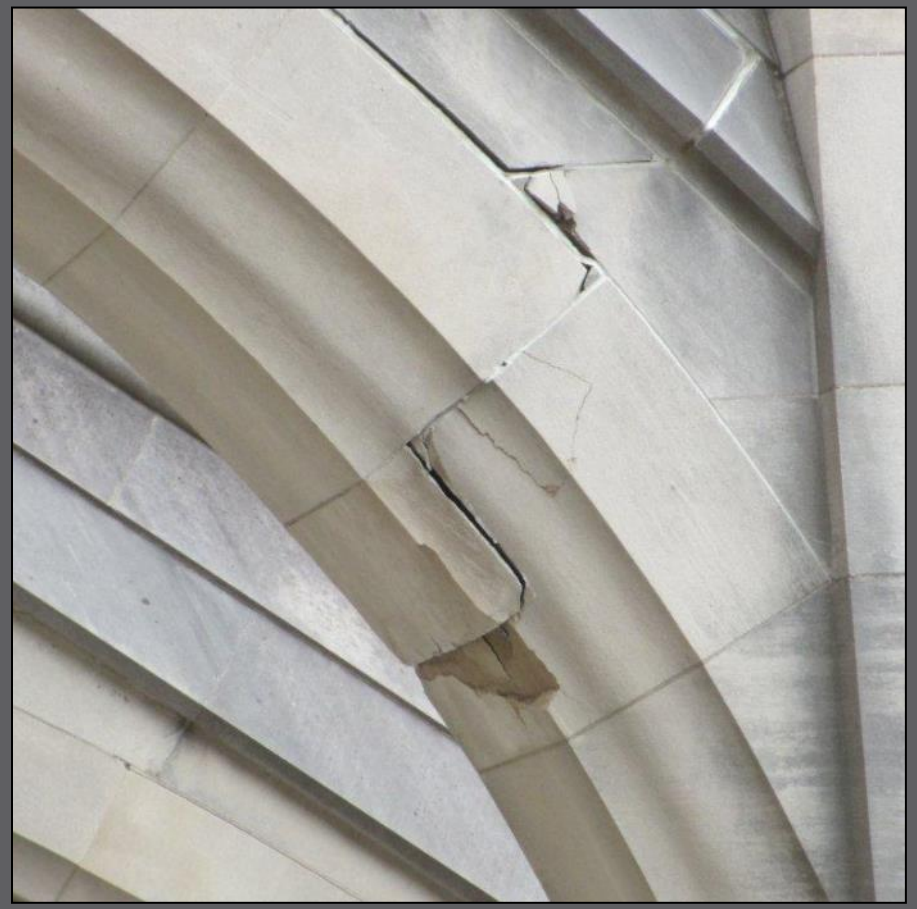
Buttresses





Seismic Damage

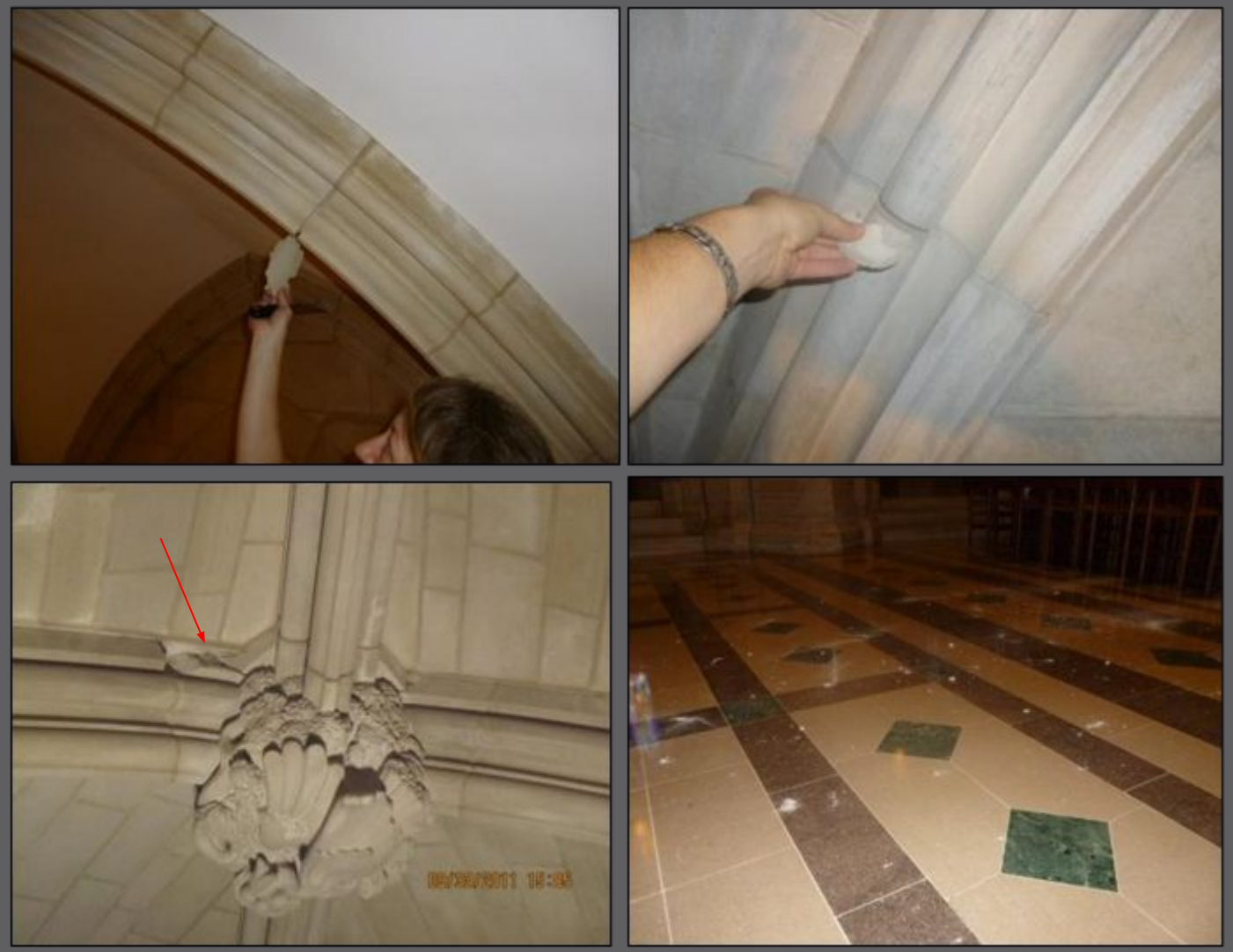
Buttresses



Seismic Damage

Interior

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



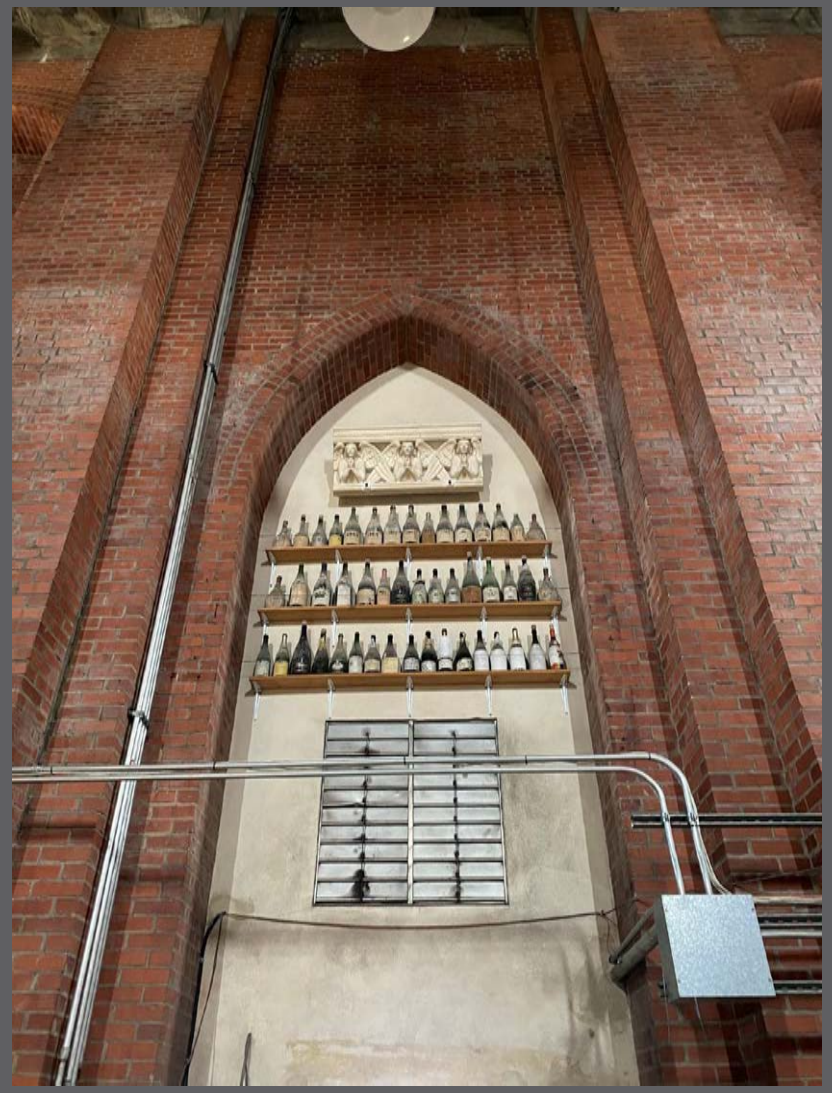
Characterization of Structure Response

- 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

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

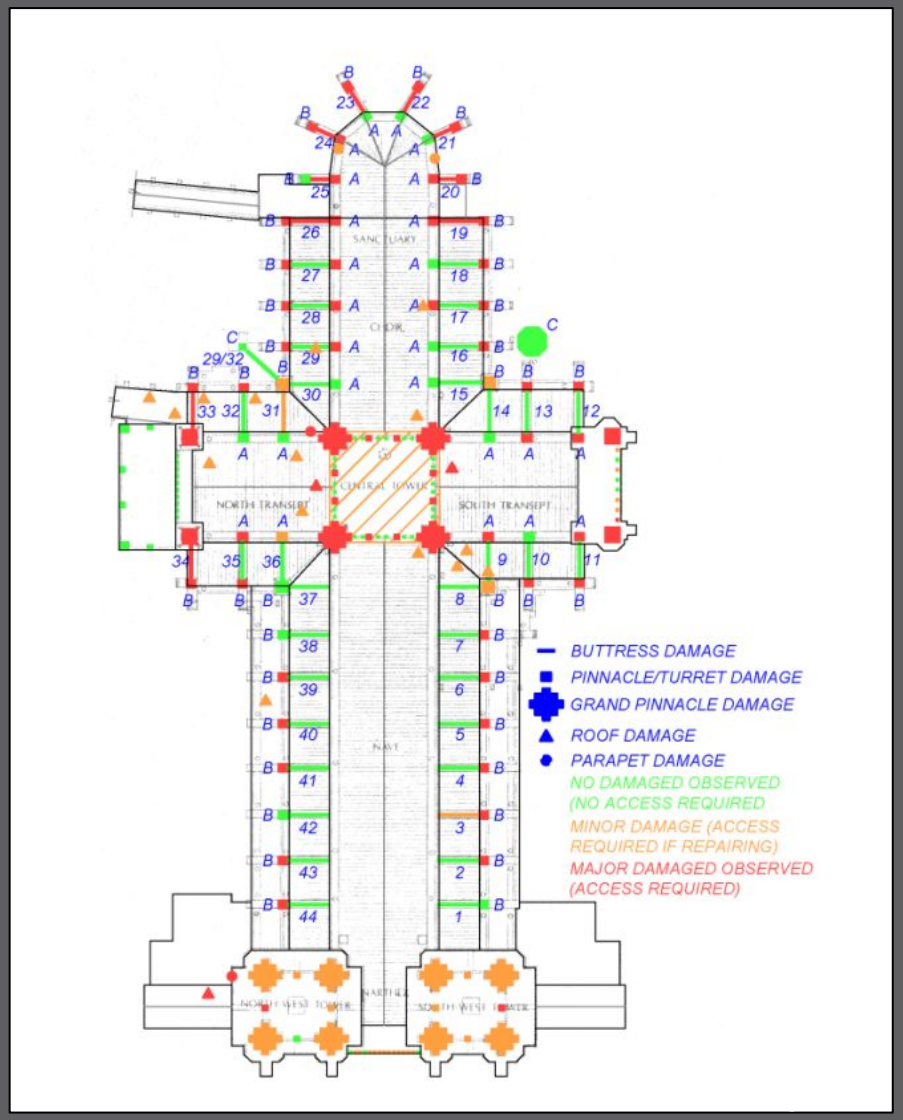


Repair Considerations

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

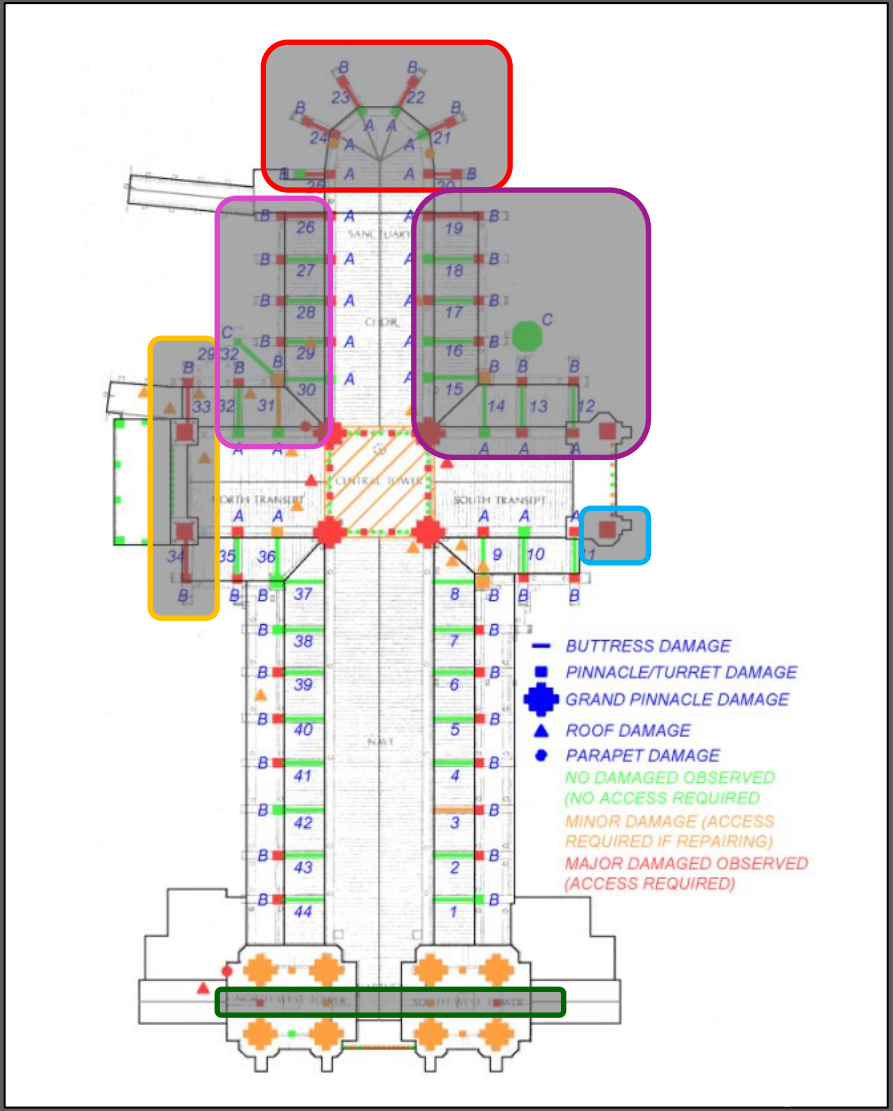
- Phasing Repairs
  - Damage Stabilized
  - Access to Damage areas with tower crane and mobile crane
  - Funding



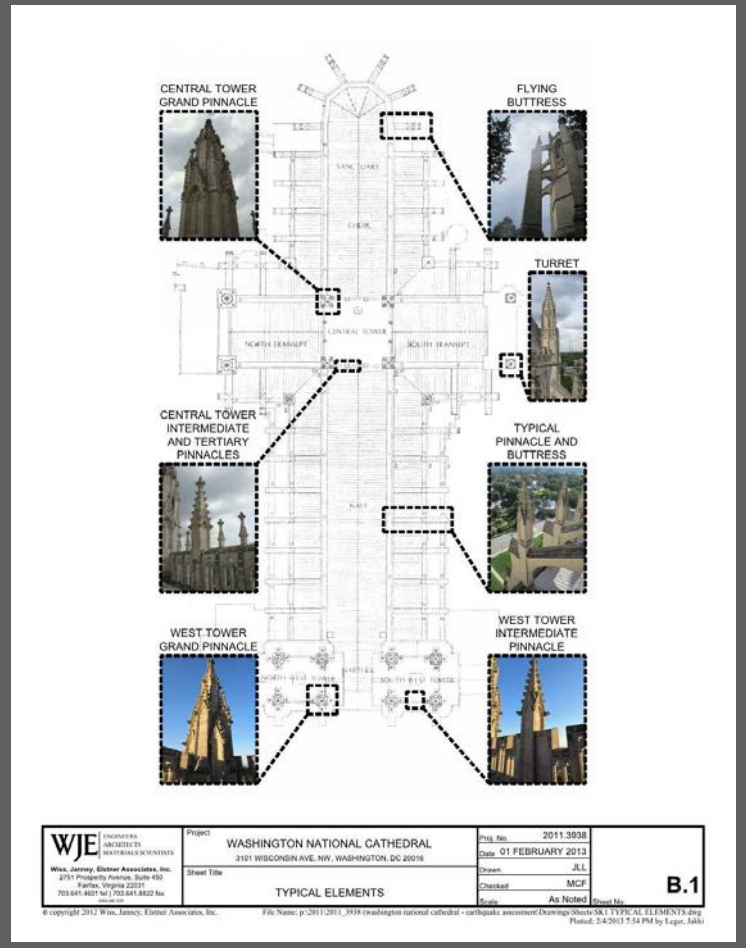
Repair Considerations

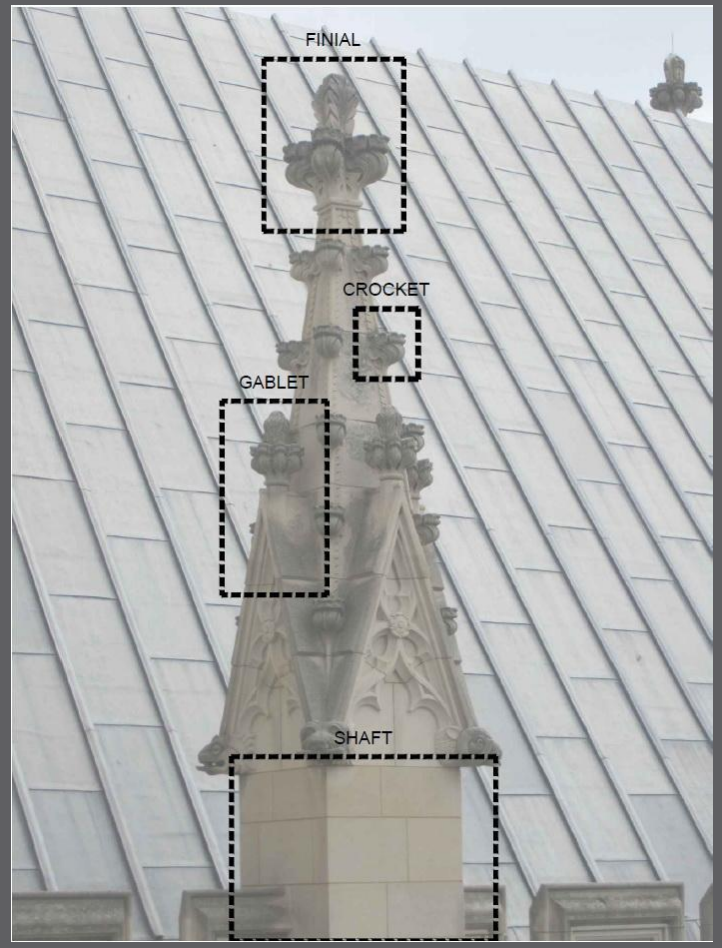
Phasing/Access

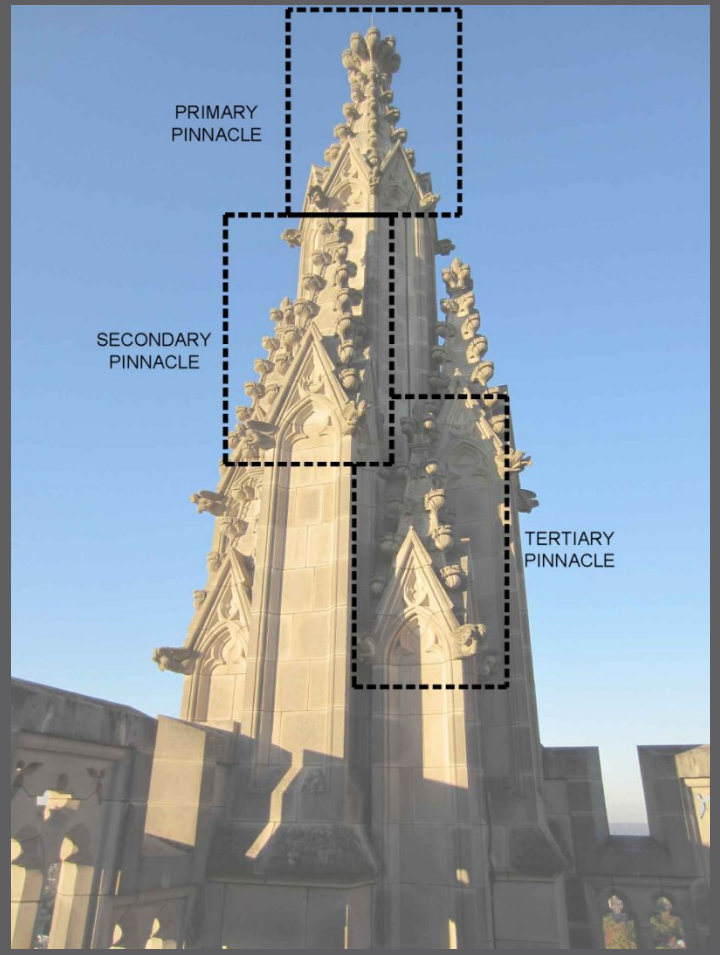
- Phase I – Interior Ceiling and Apse Buttresses
- Phase IIA – North Transept
- Phase IIB – West Towers
- Phase IIC – South Transept Dismantling
- Phase IID – Garth
- Phase IIE – Way of Peace & SE Turret



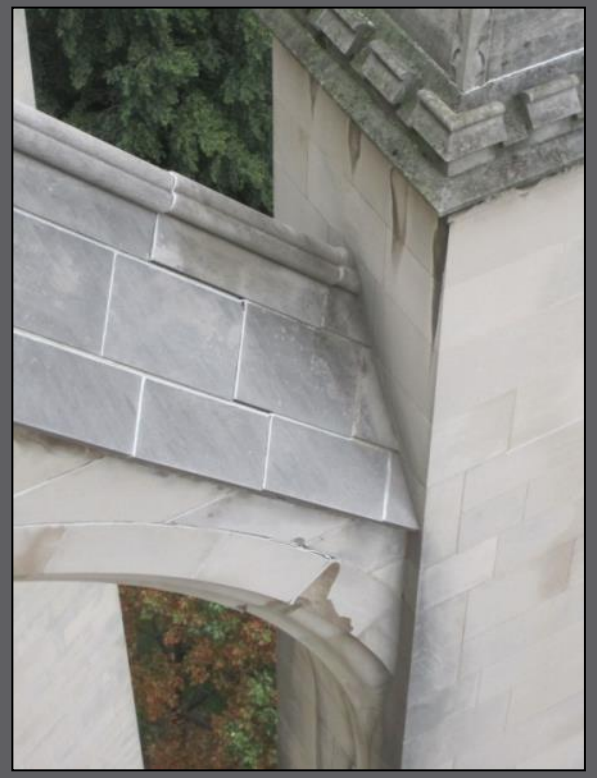
Repair Considerations

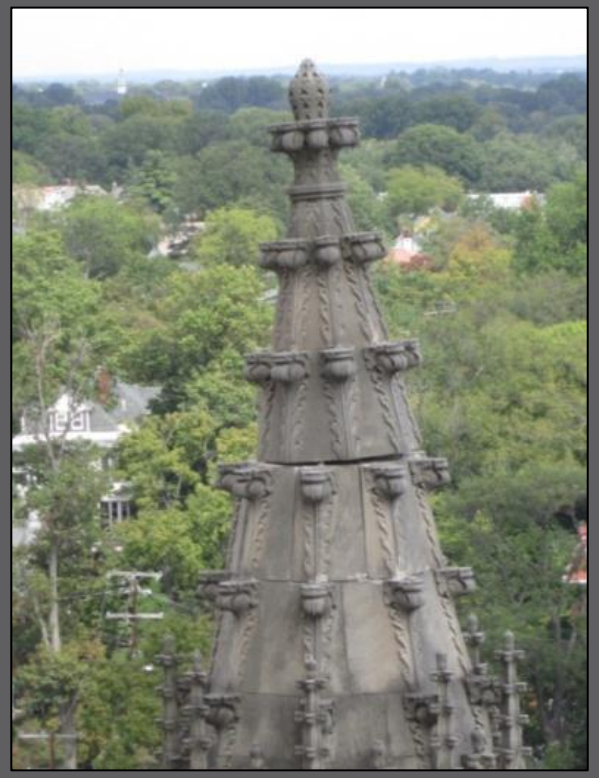






Structural Analysis





- 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

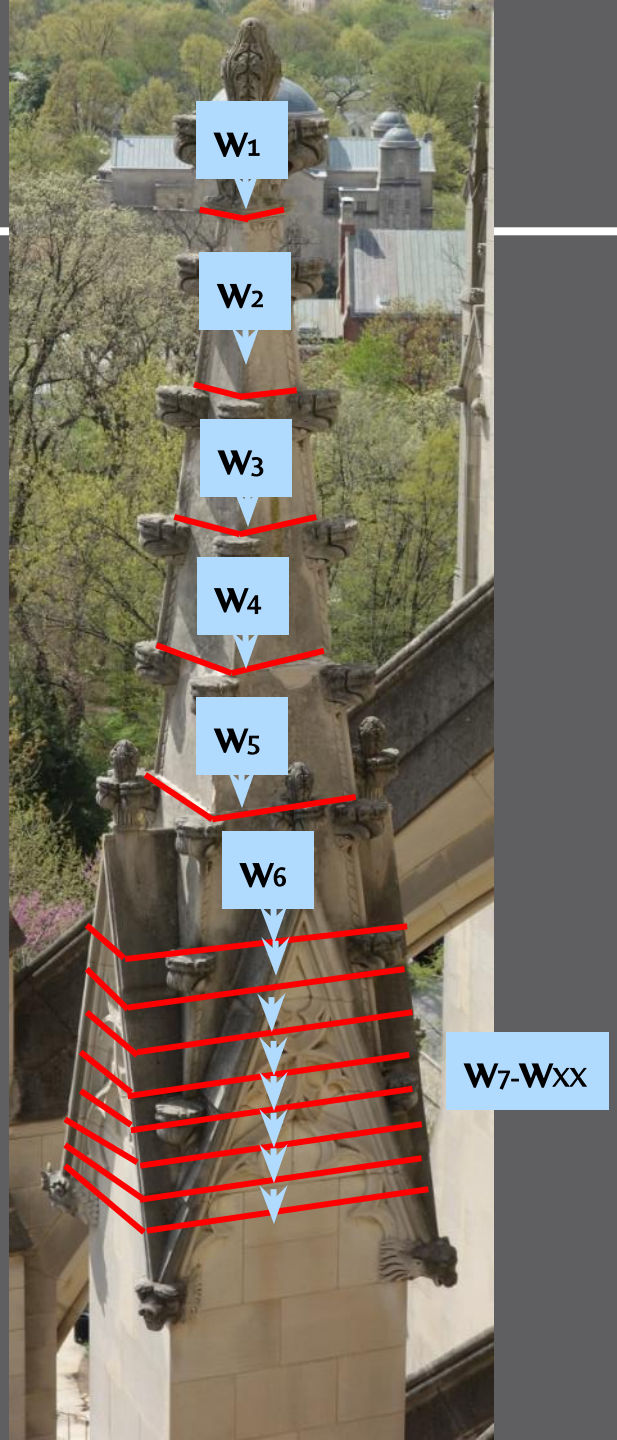
Engineering for Preservation

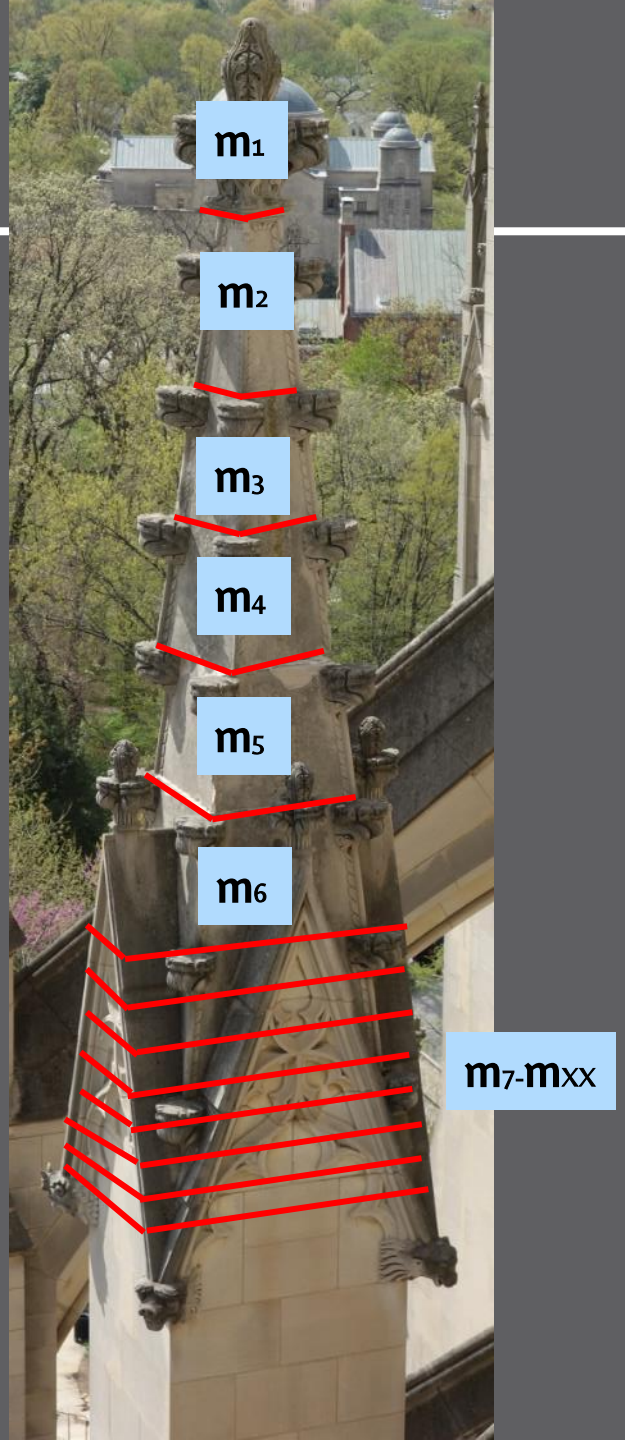
- Identify the critical vulnerabilities of the existing construction, and develop "surgical" methods of intervention to mitigate them

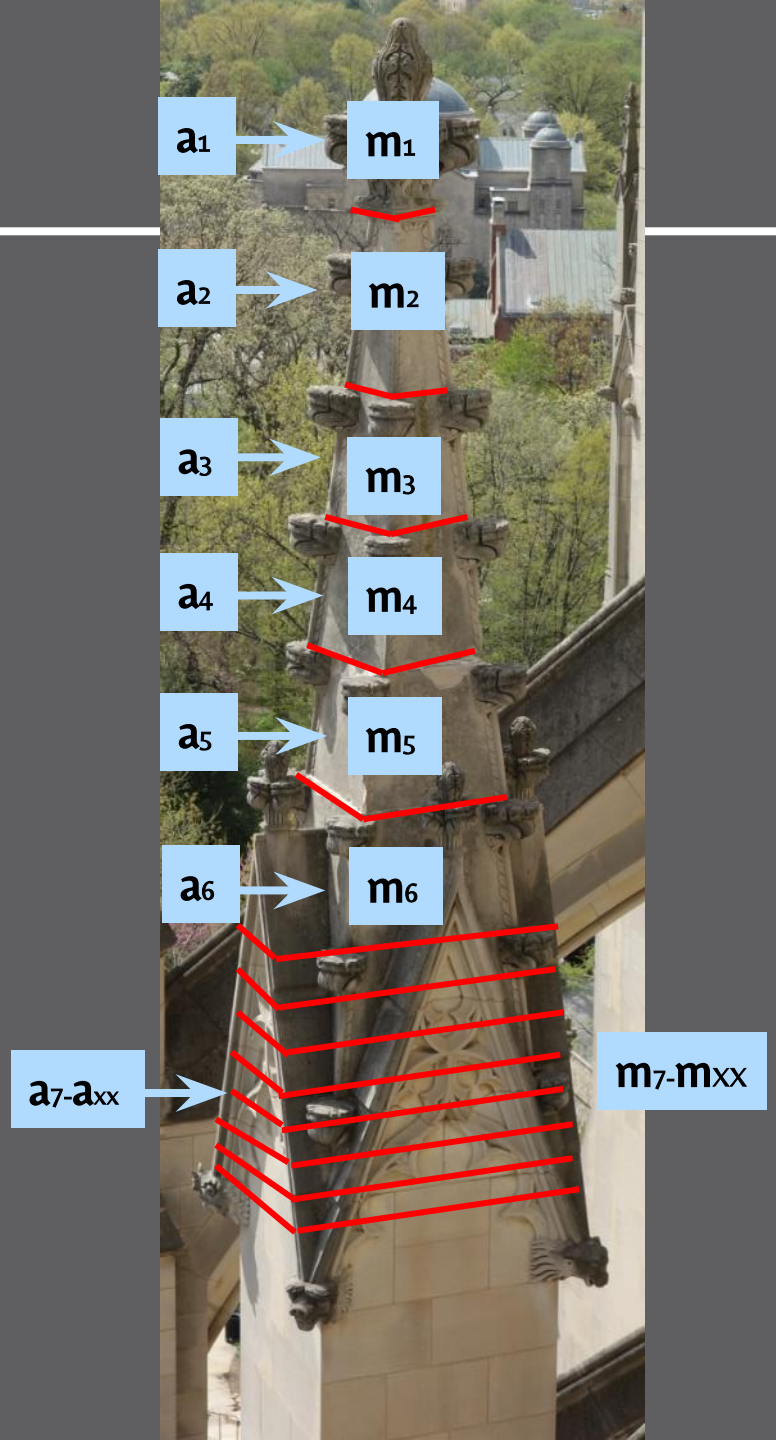
- Identify/credit the positive attributes of the existing construction, and develop "surgical" approaches to leverage them

- 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.


Solid Stone courses
Brick coursing with stone veneer


W1
W2
W3
W4
W5
W6
W7-WXX


m1
m2
m3
m4
m5
m6
m7-mXX


a1
m1
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m2
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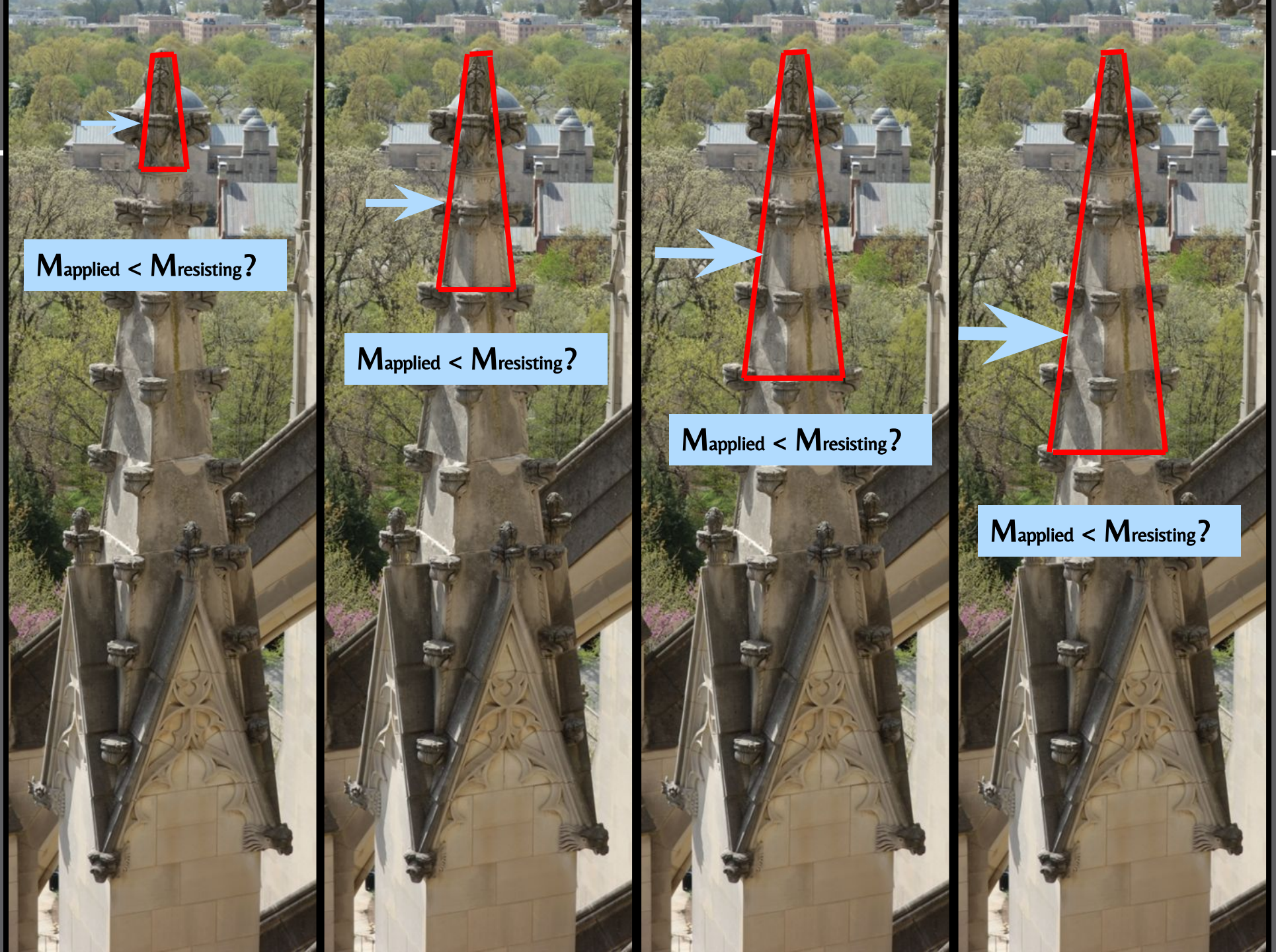
a4
m4
a5
m5
a6
m6
a7-axx
m7-mxx


$M_{applied} < M_{resisting}$?
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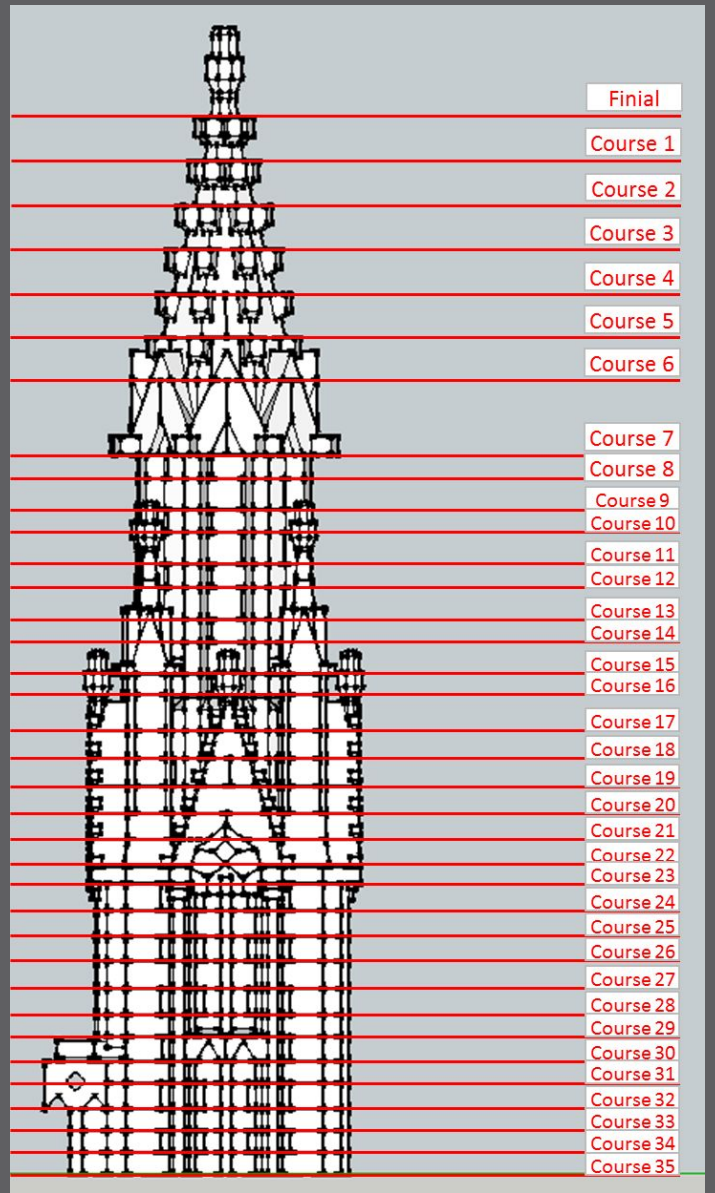
Grand Pinnacles



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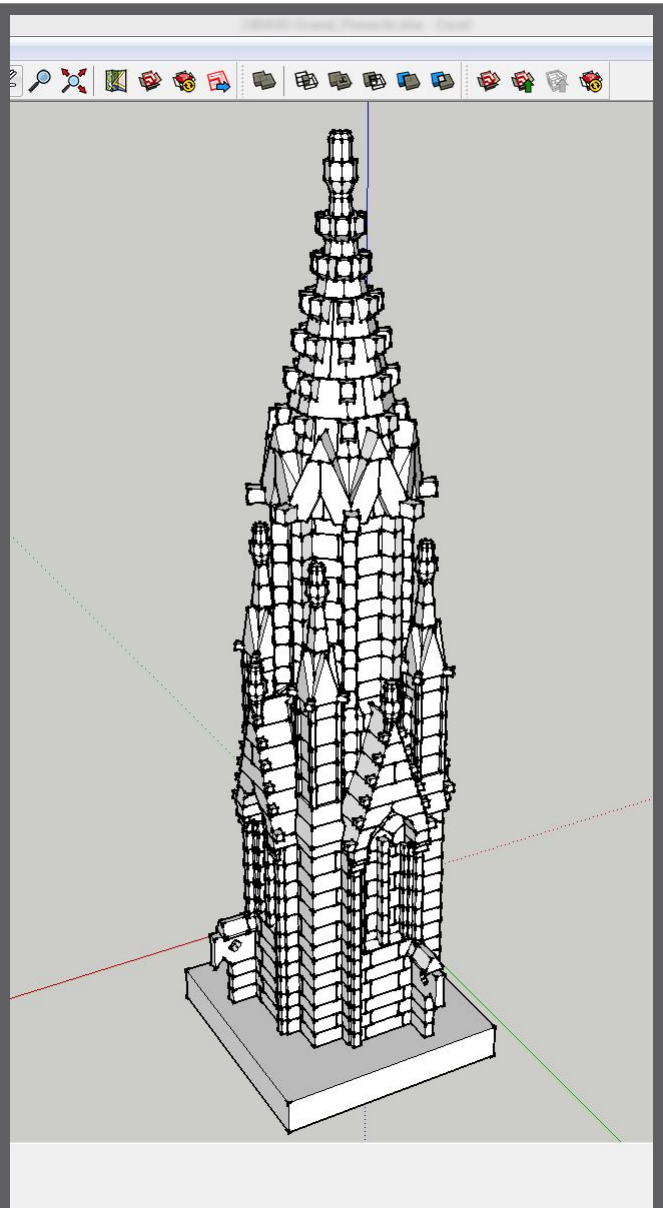

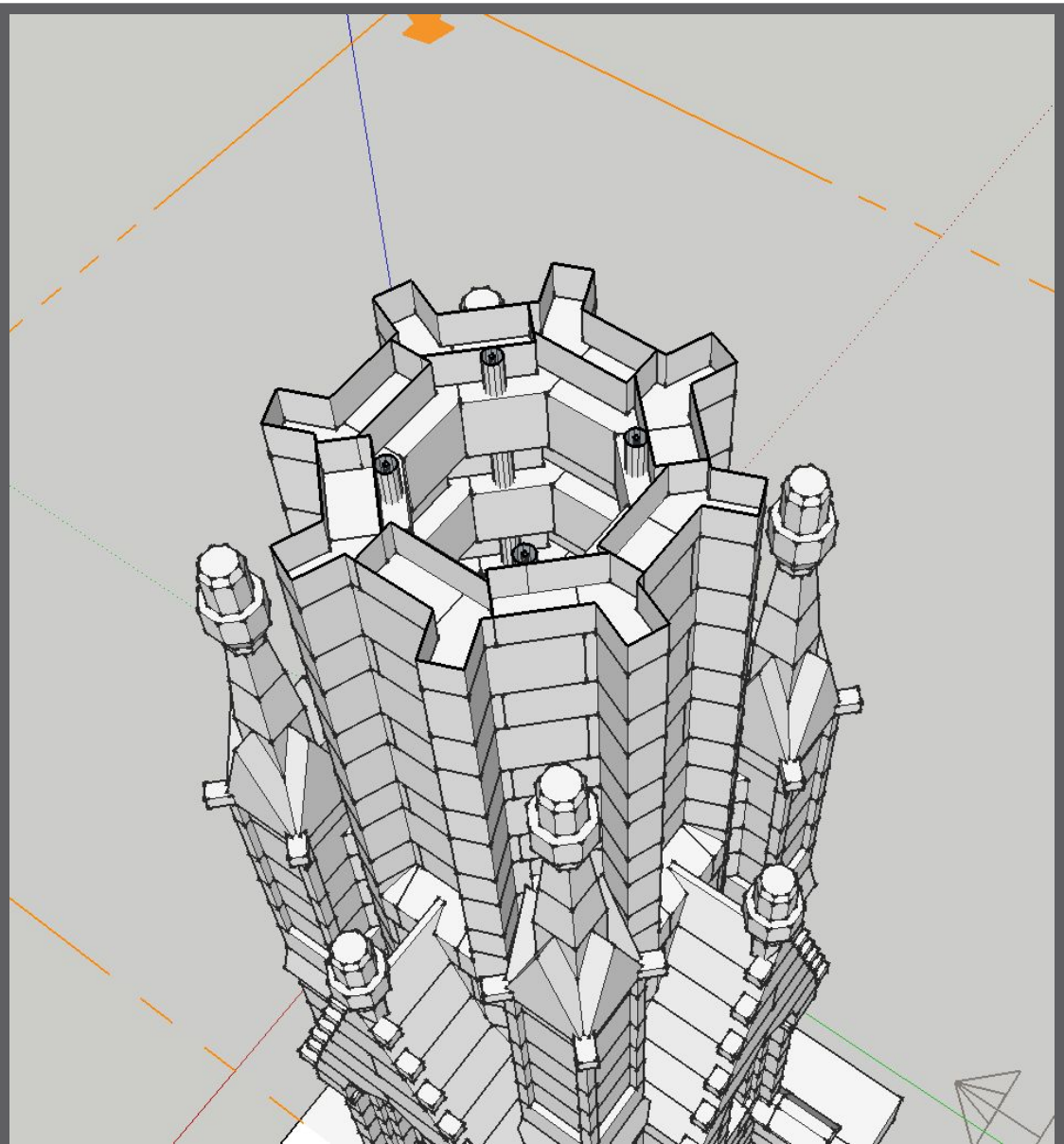

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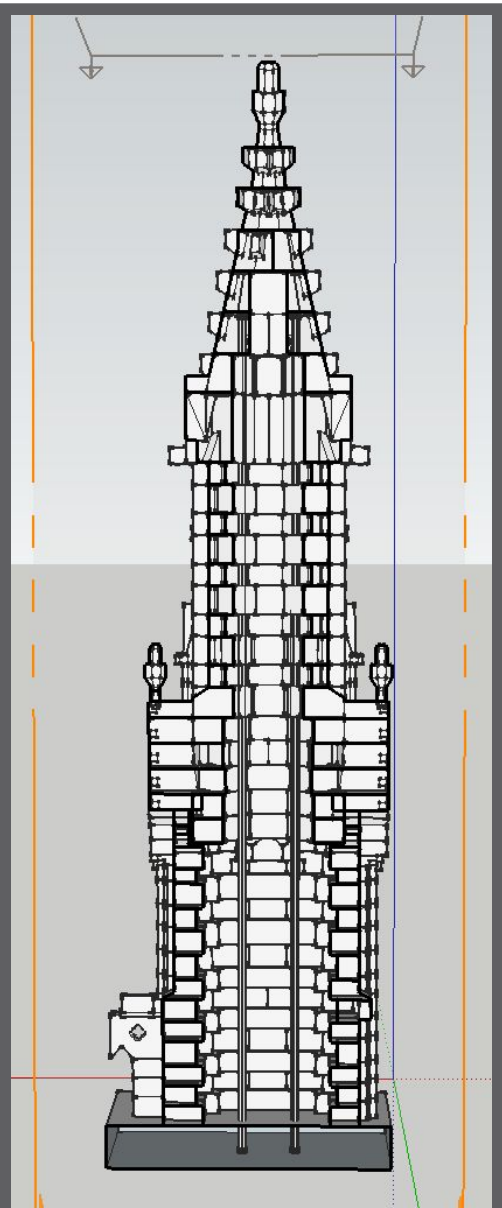
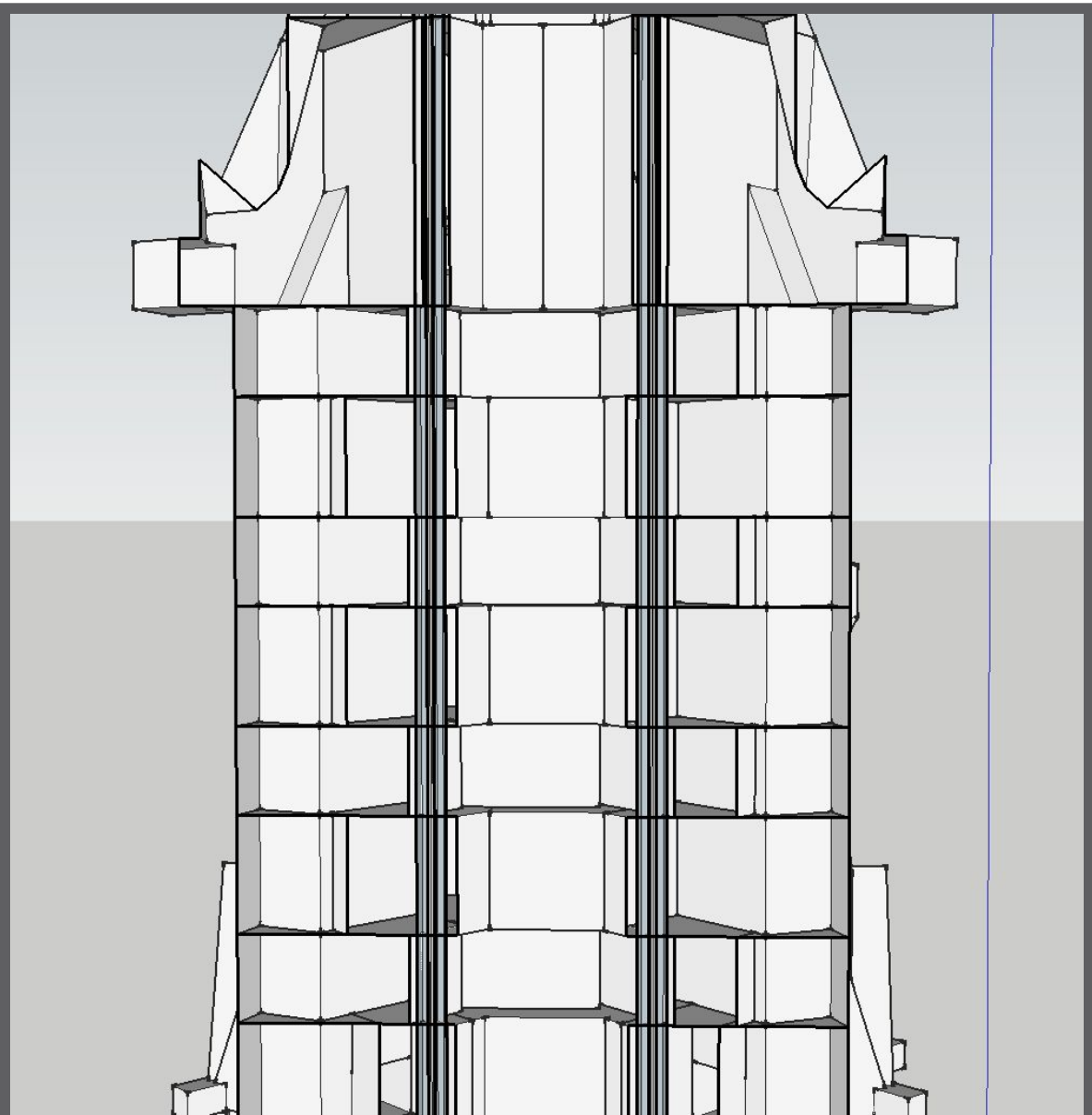
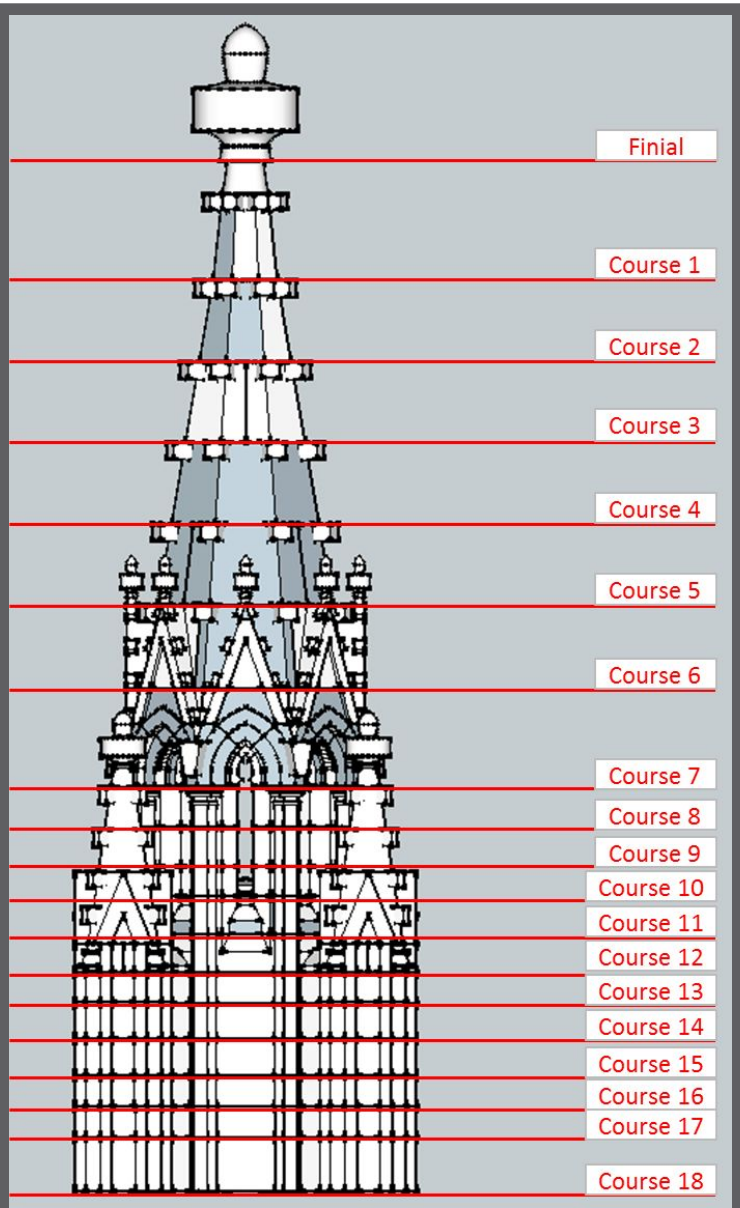




Turrets at the South Transept



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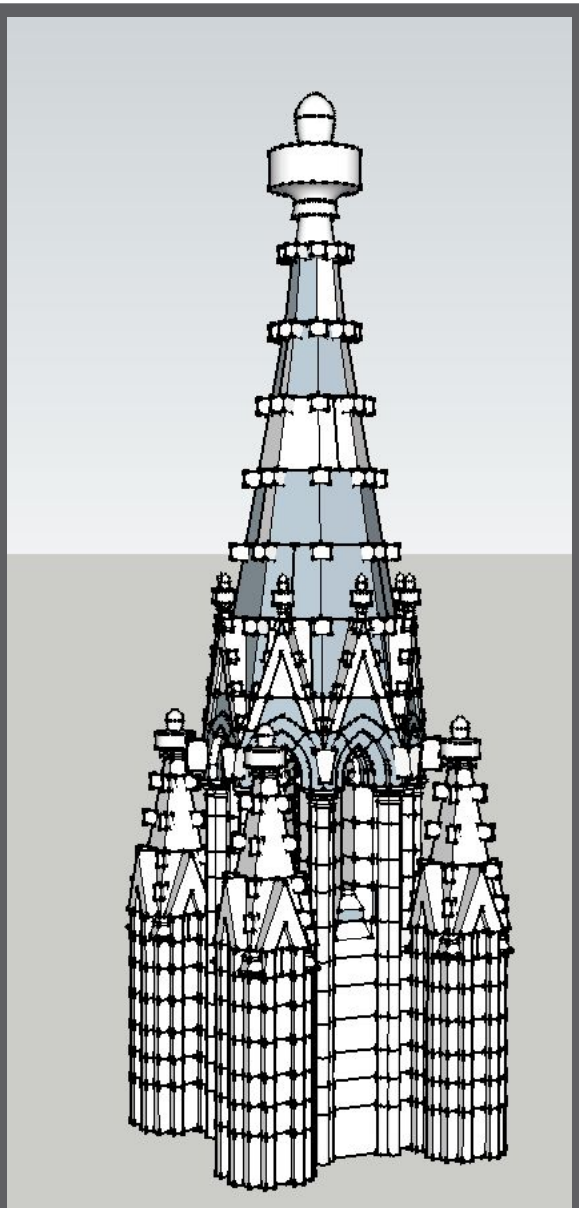

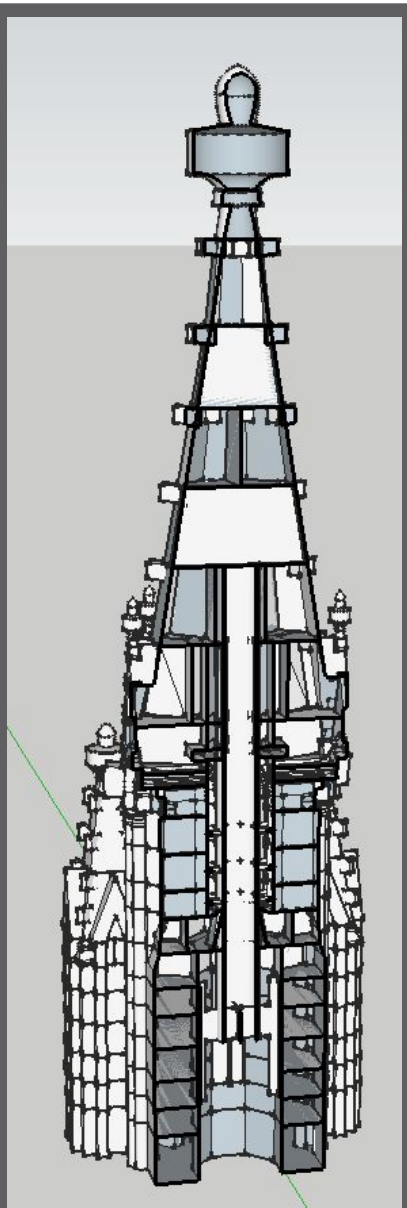

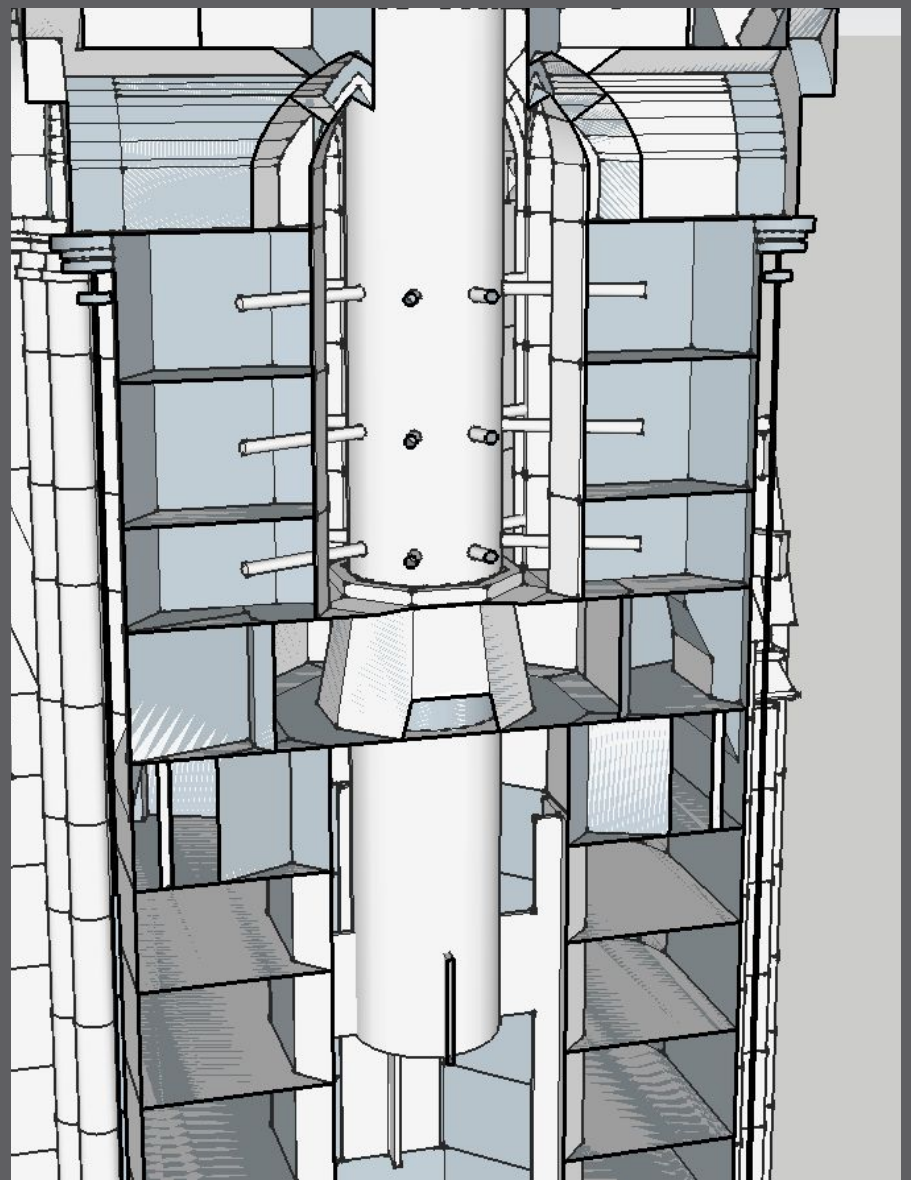

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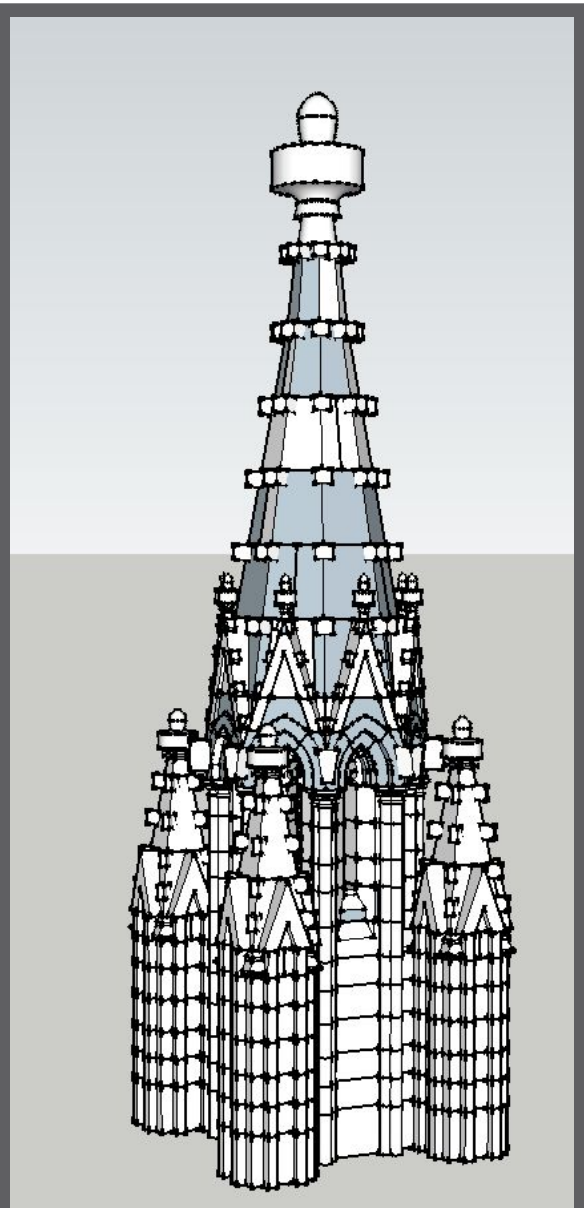

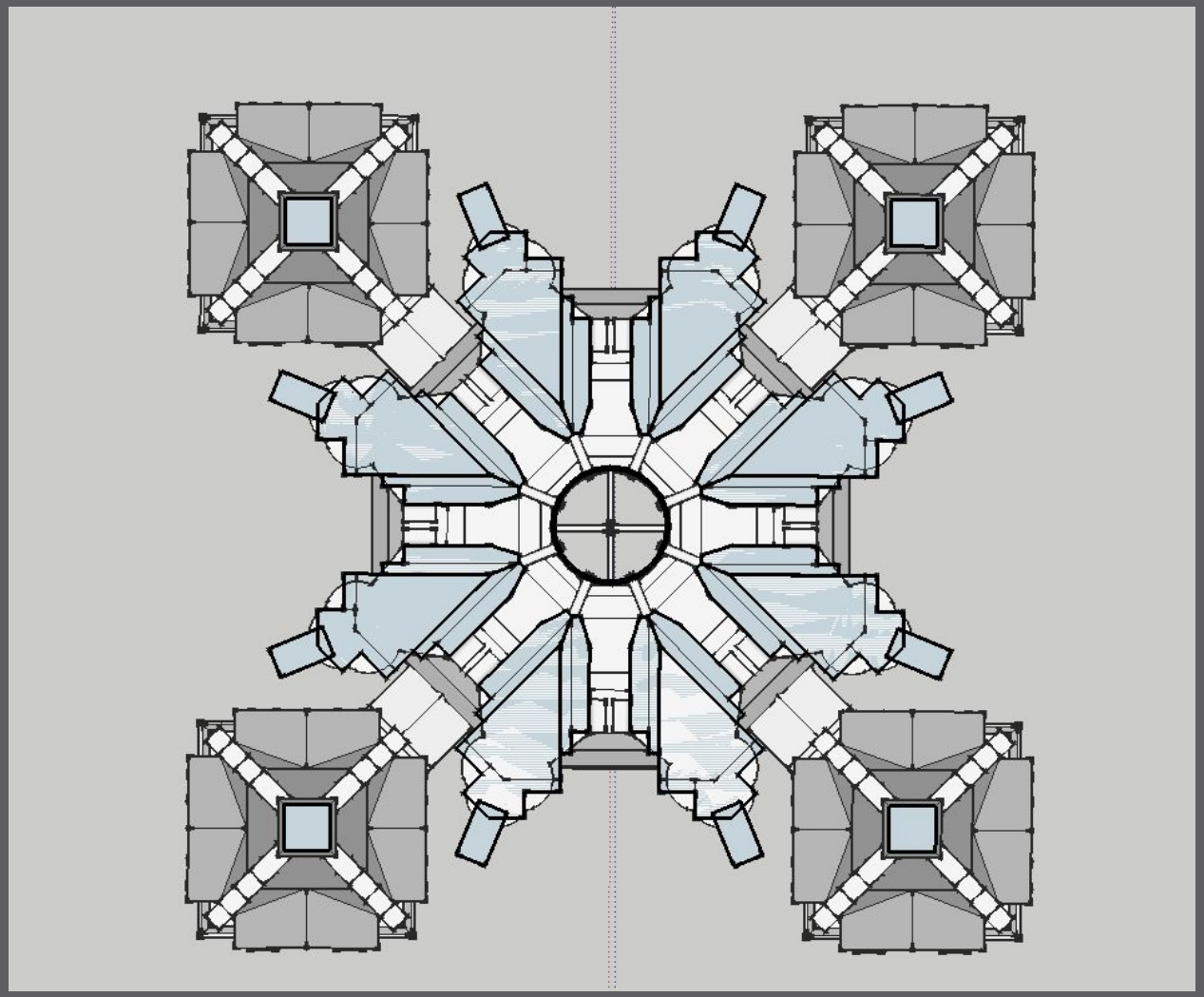

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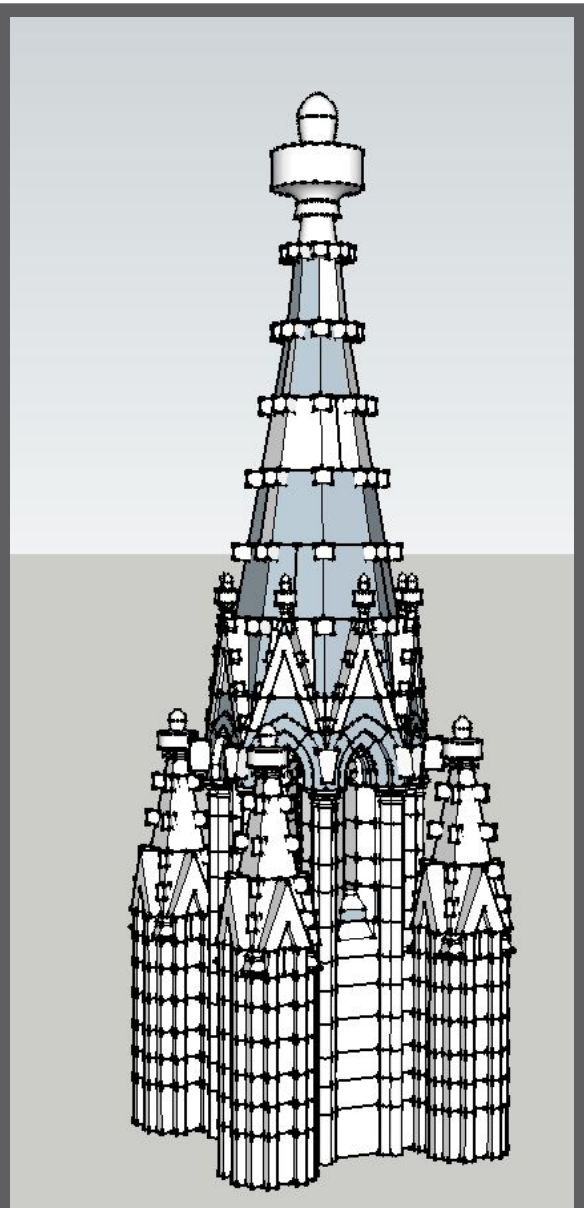

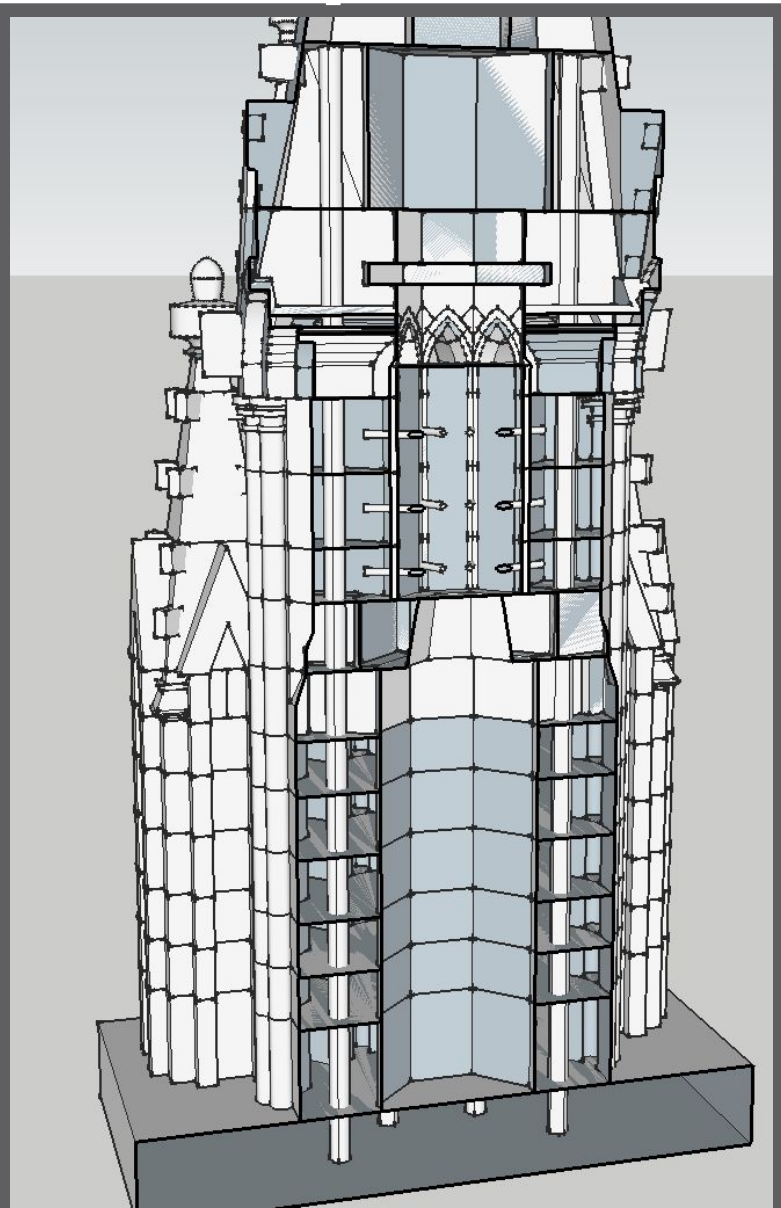

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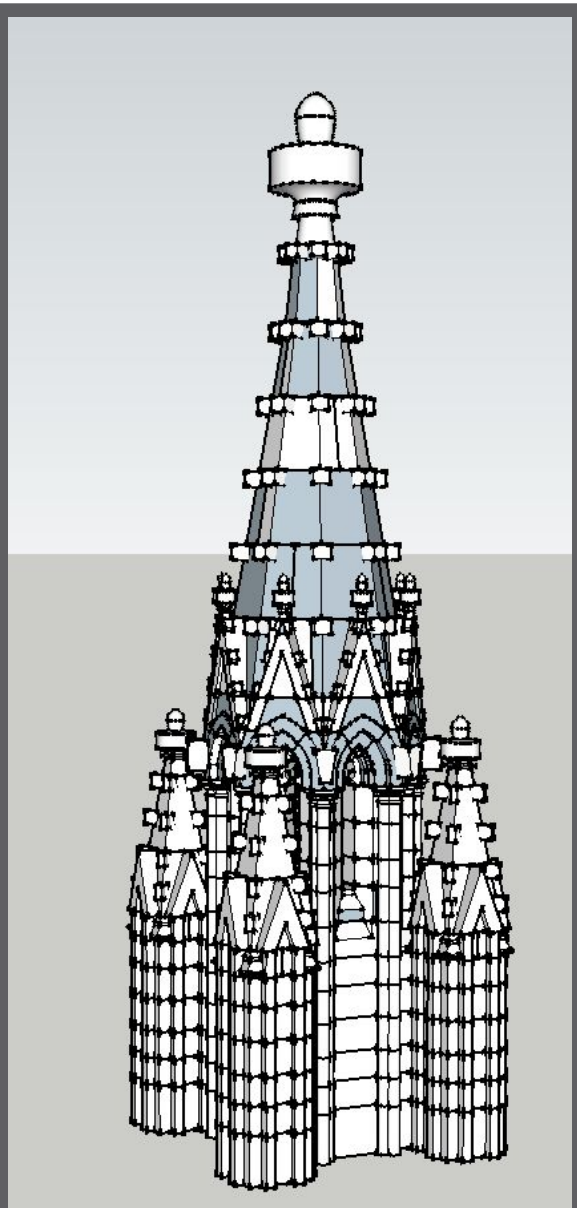
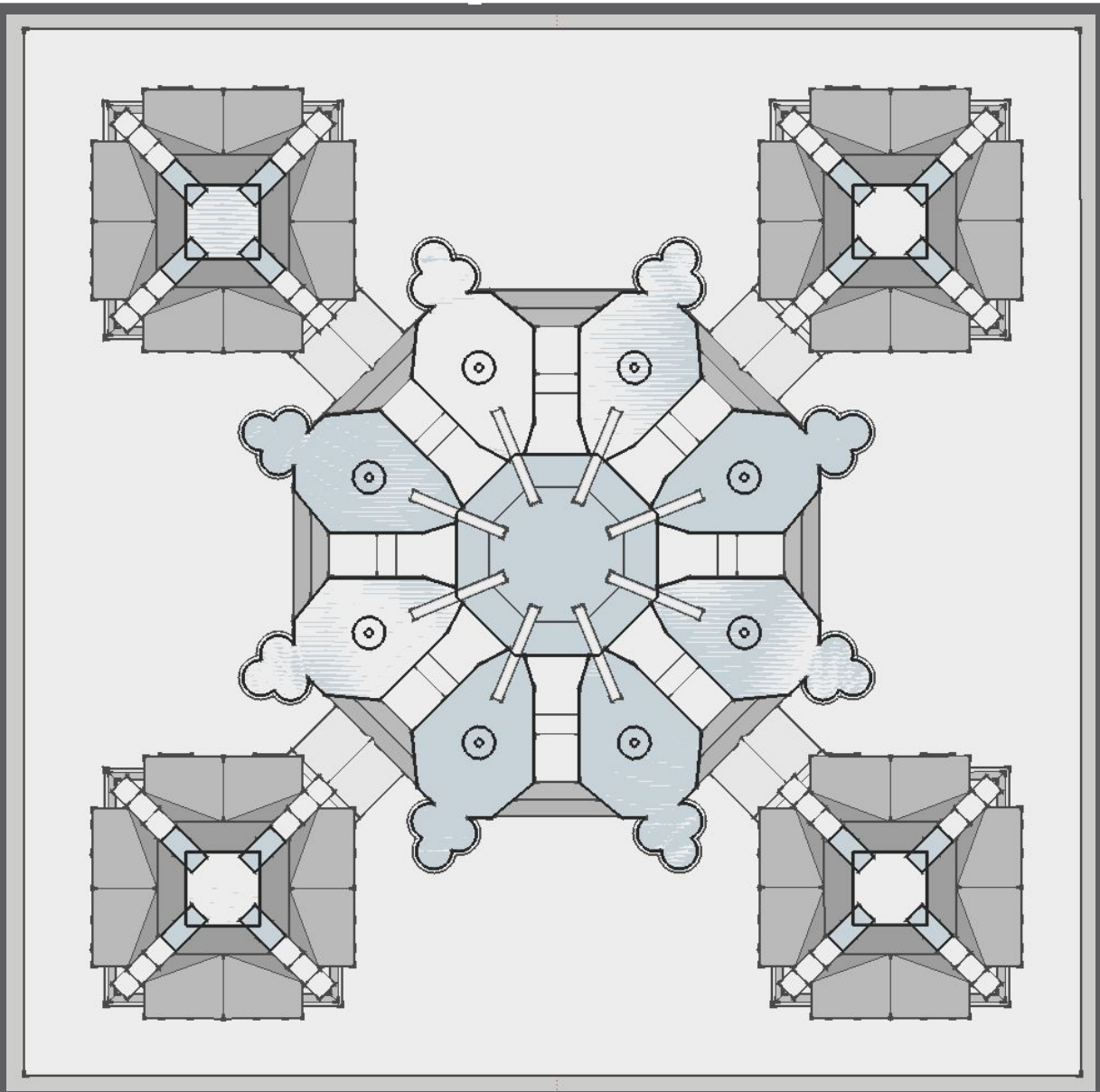
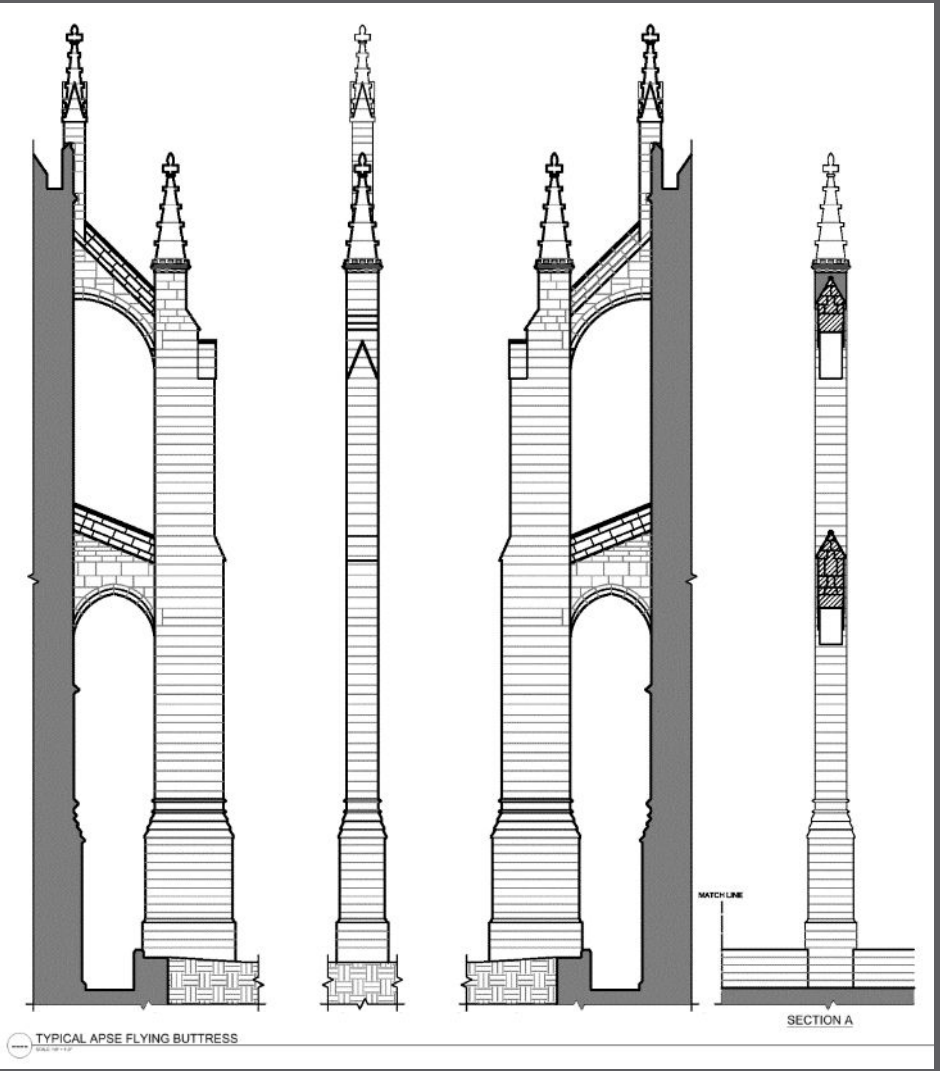





ENTRANCE

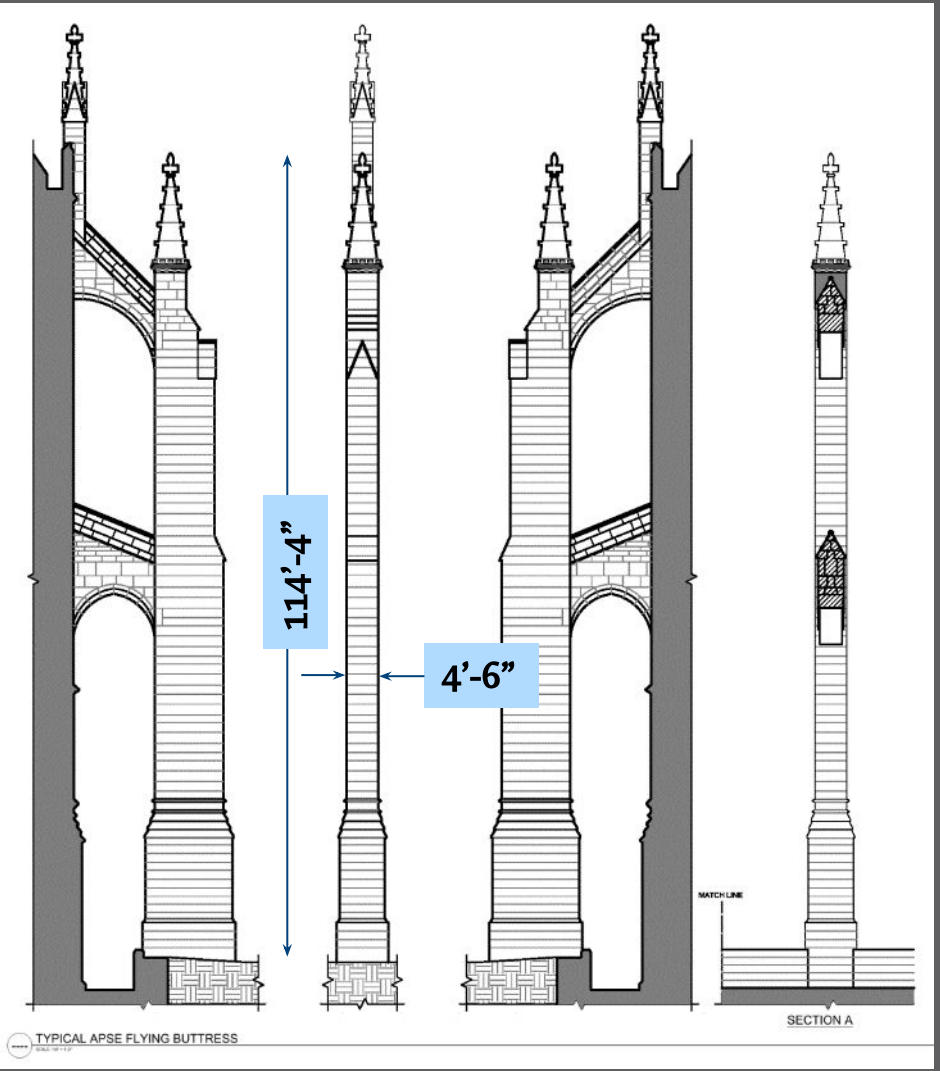
Repair Implementation

Apse Buttress Elevations



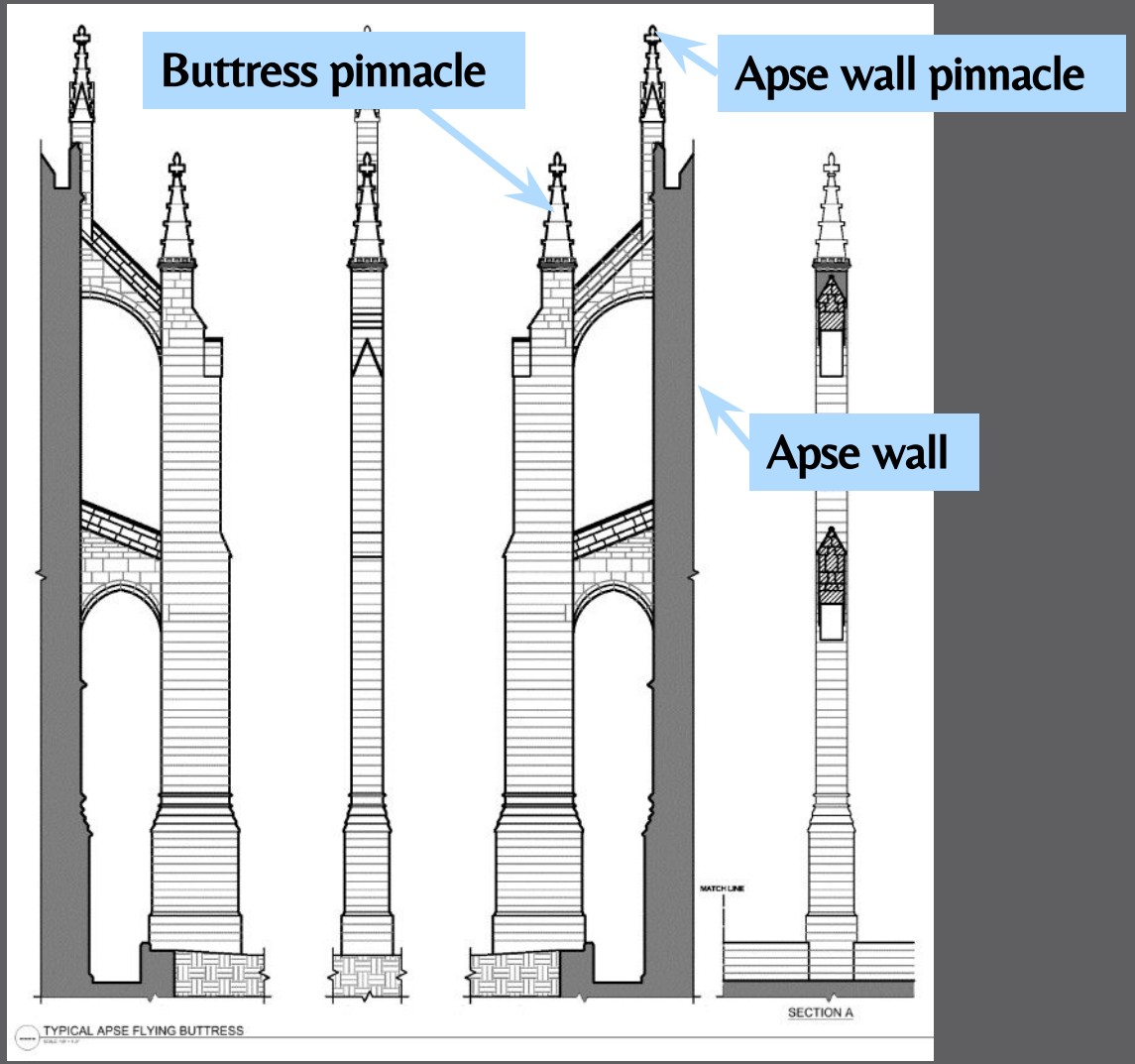
Repair Implementation

Apse Buttress Elevations



Repair Implementation

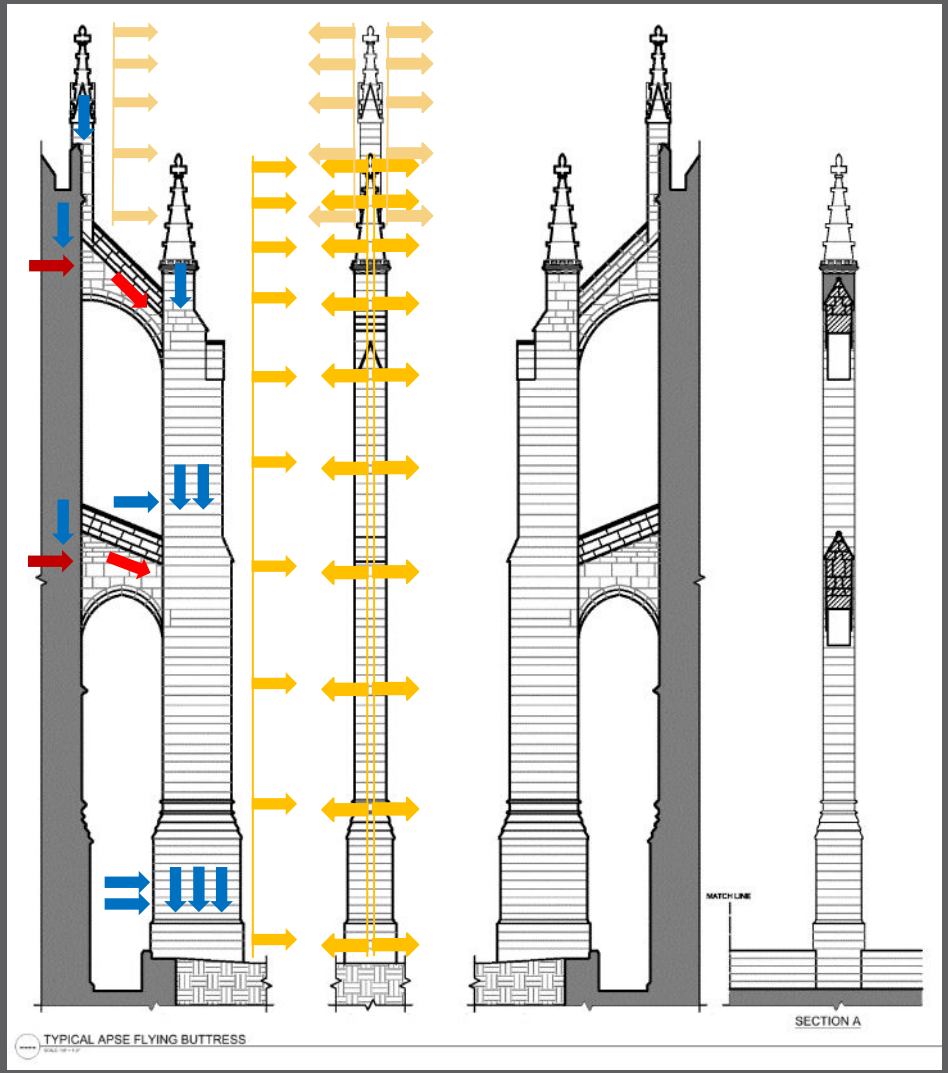
Apse Buttress Elevations



- 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

Repair Implementation

Gravity and Wind Forces



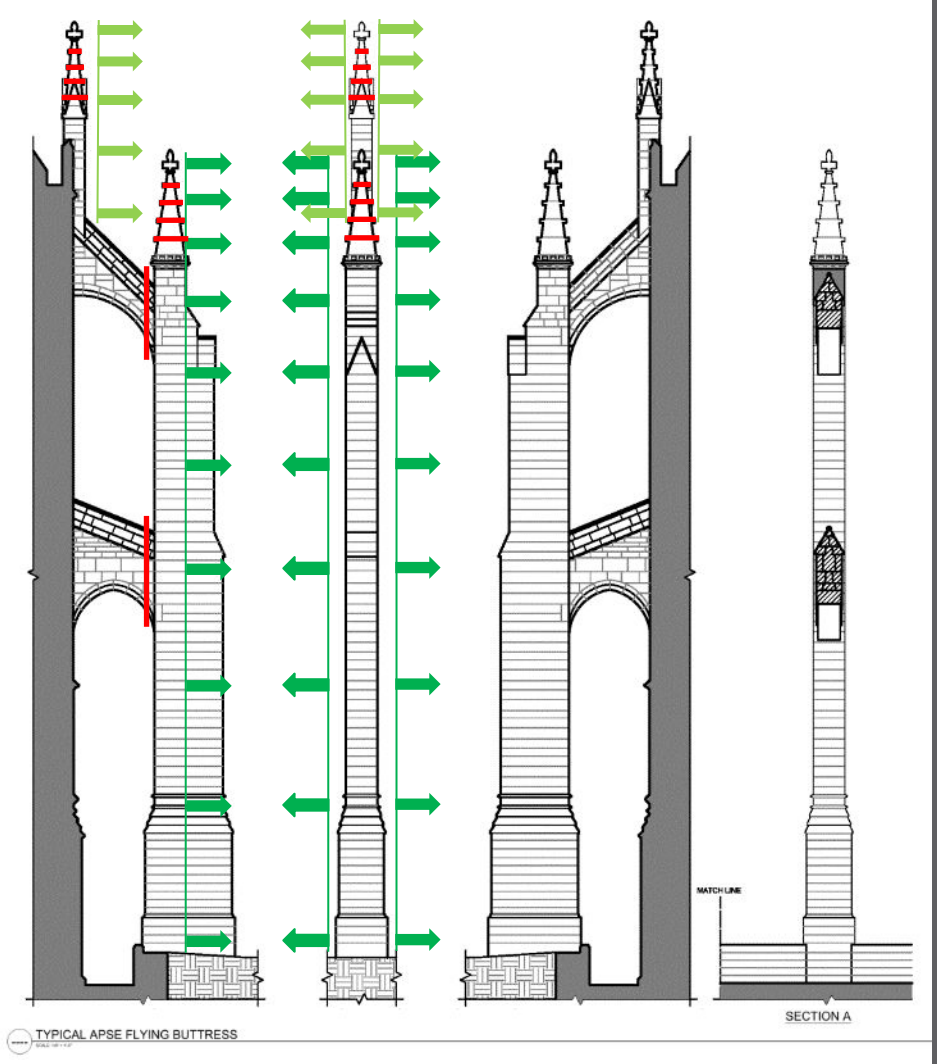
= gravity

= wind

= thrust from wall

Repair Implementation

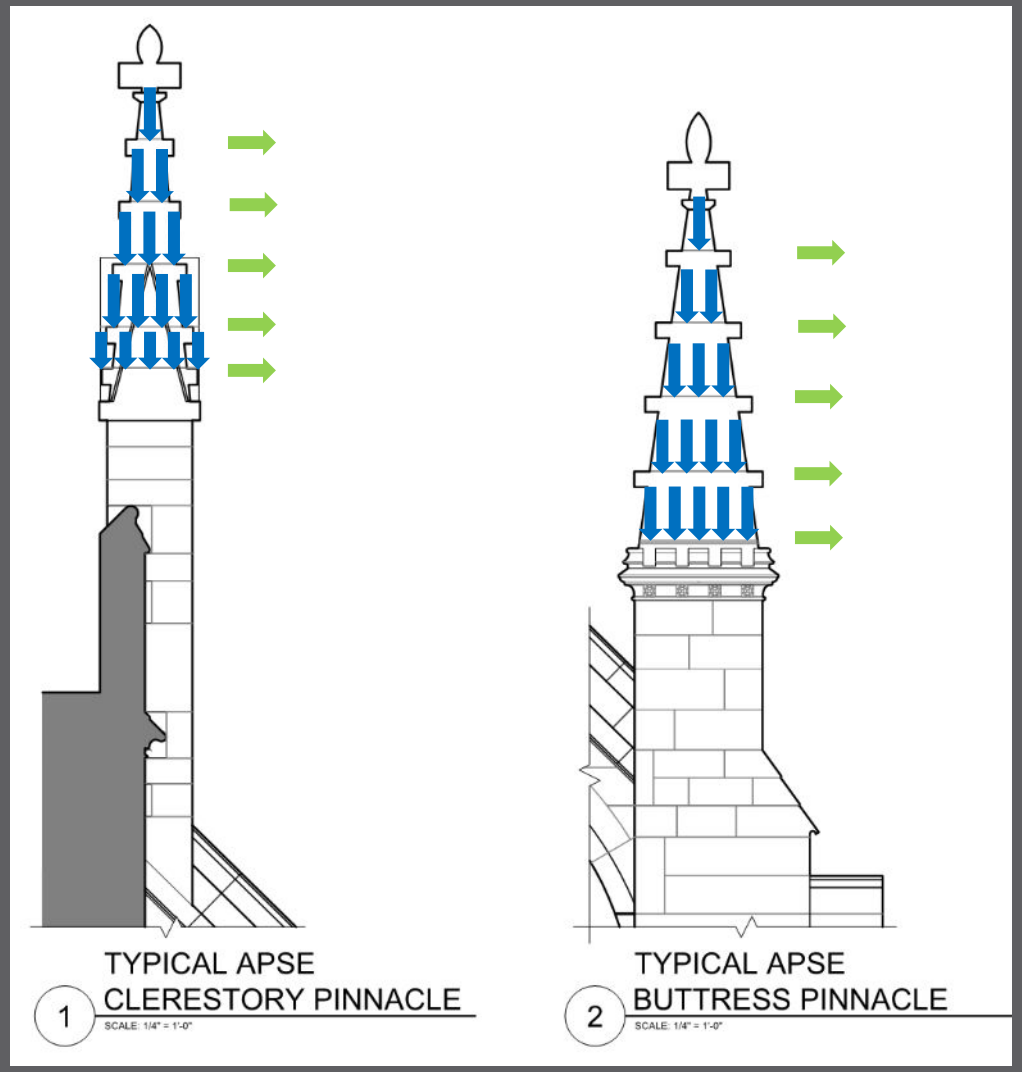
Seismic Forces



= Seismic

= Critical section

Repair Implementation

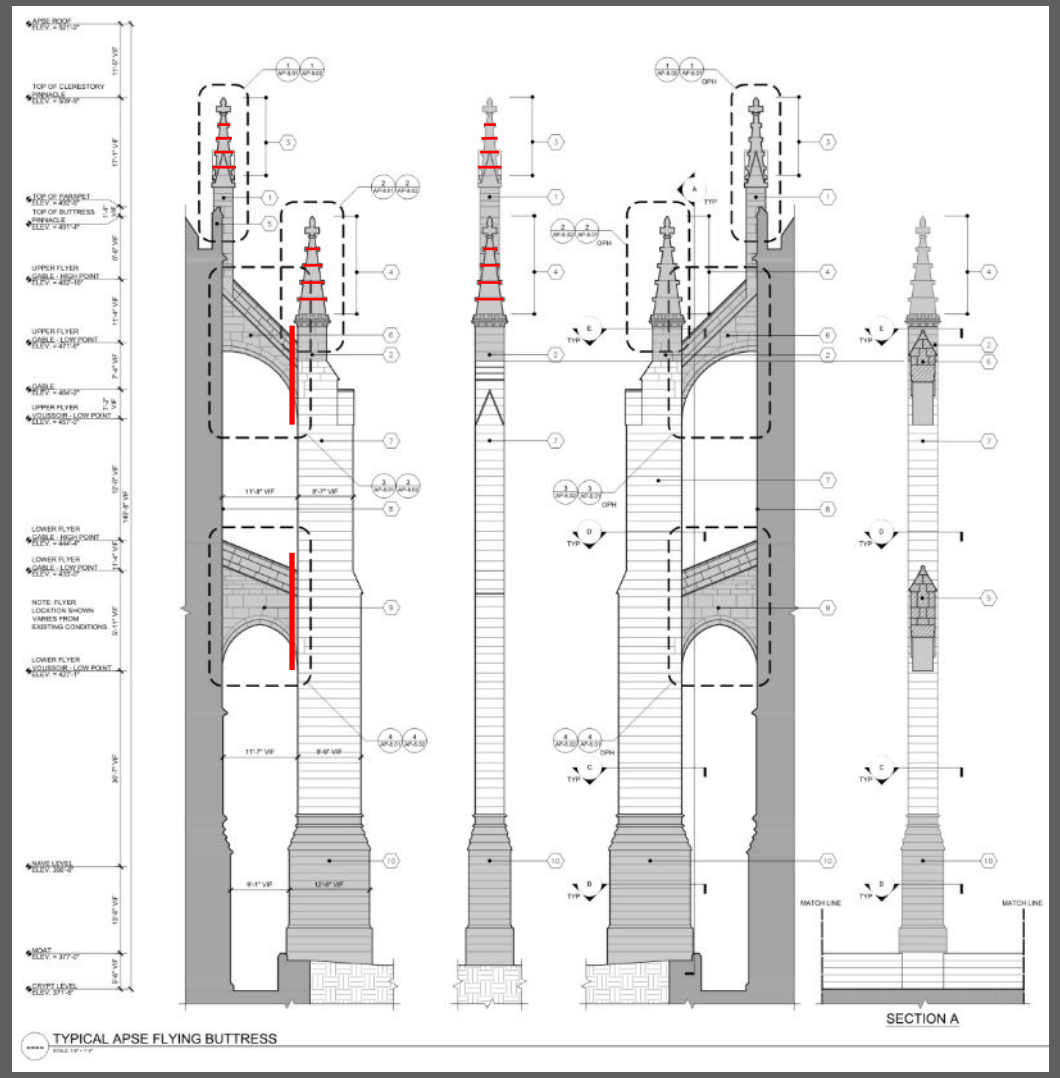


What is the appropriate repair to damaged buttress pinnacles?

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

Repair Implementation

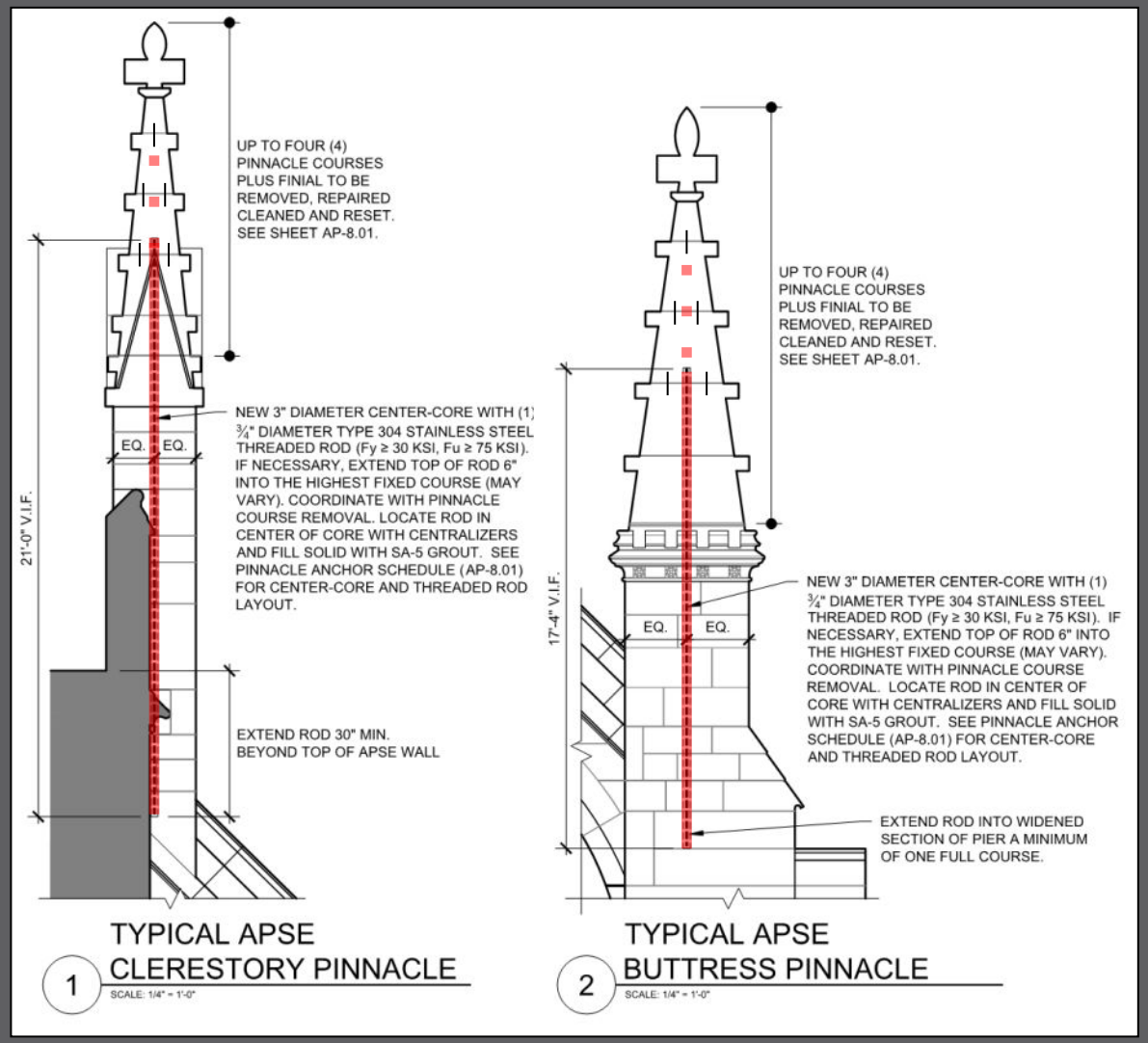
Strengthening



= Critical section

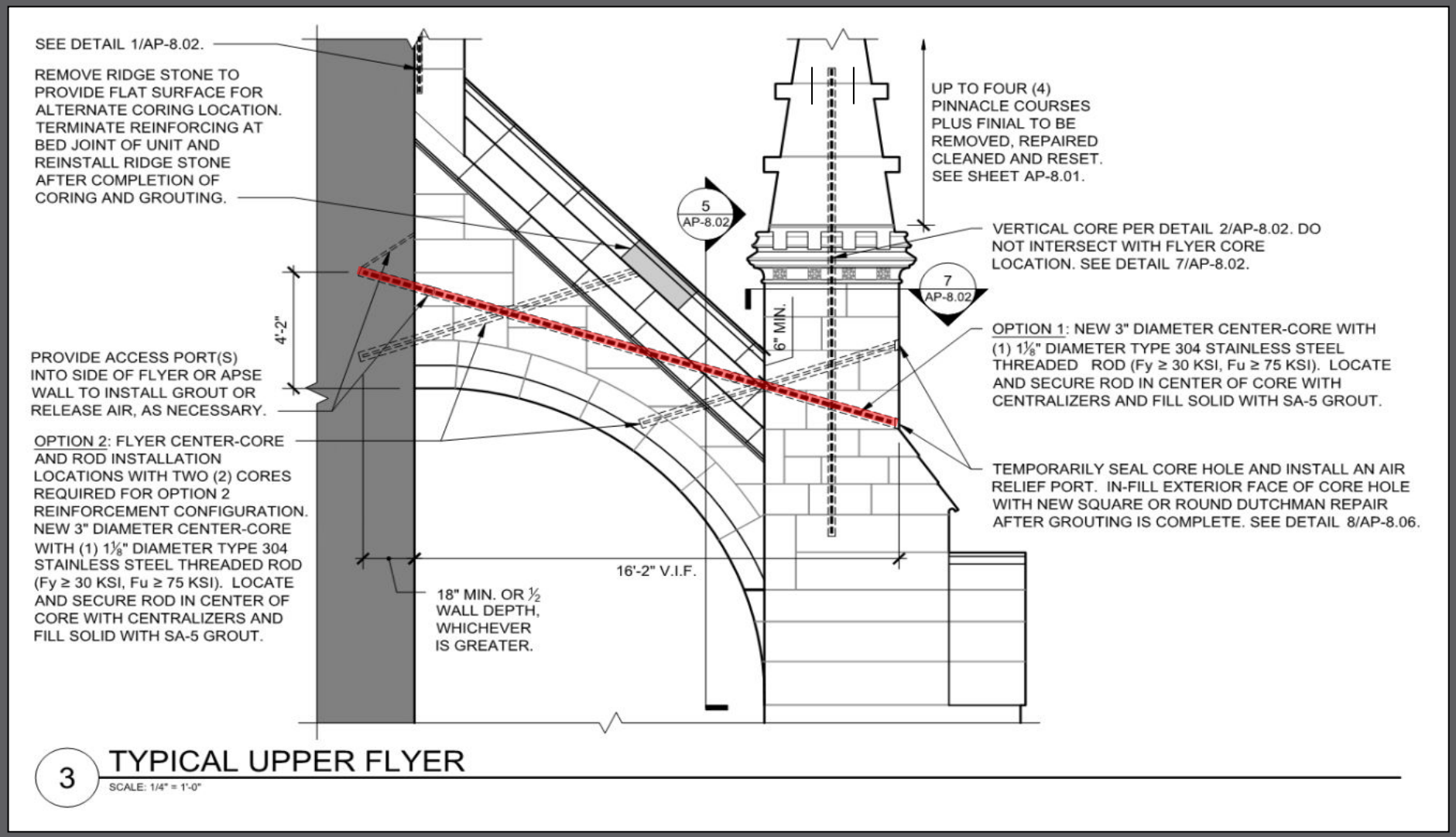
Repair Implementation

Strengthening - Pinnacles



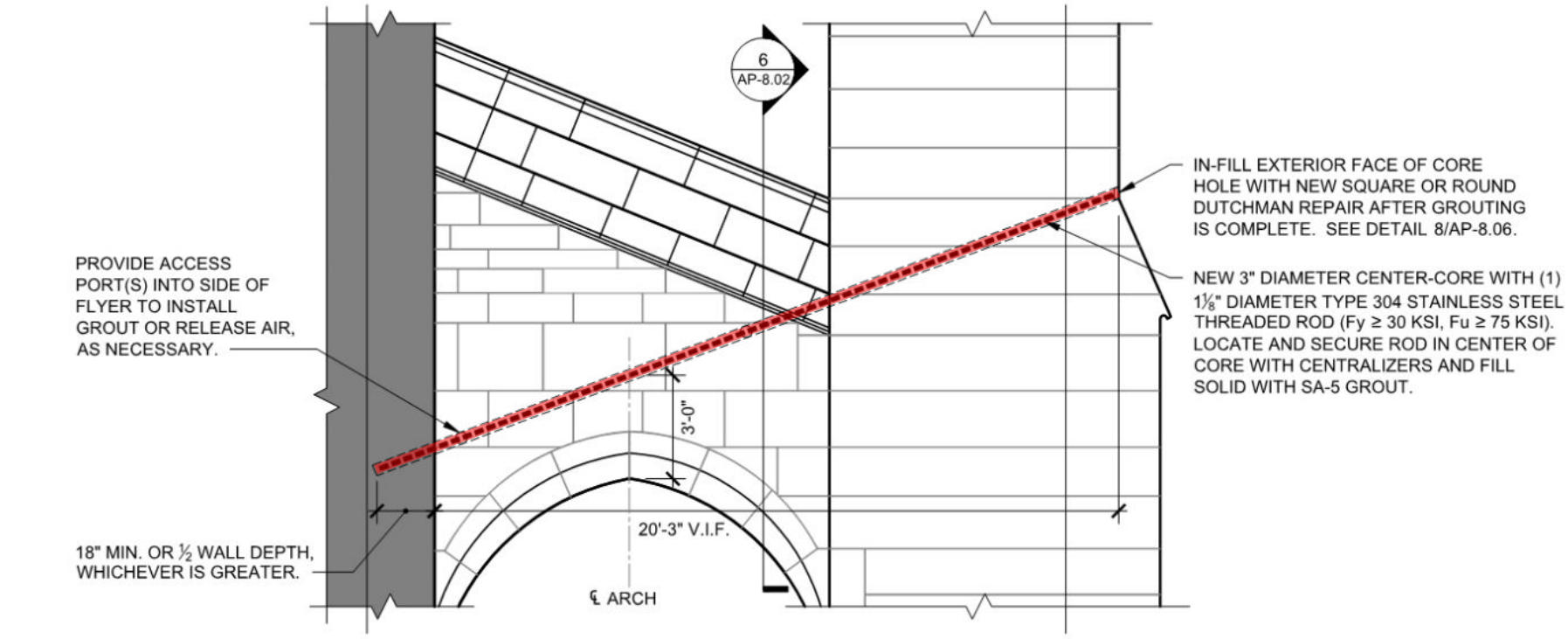
Repair Implementation

Strengthening – Upper Flyer



Repair Implementation

Strengthening – Lower Flyer

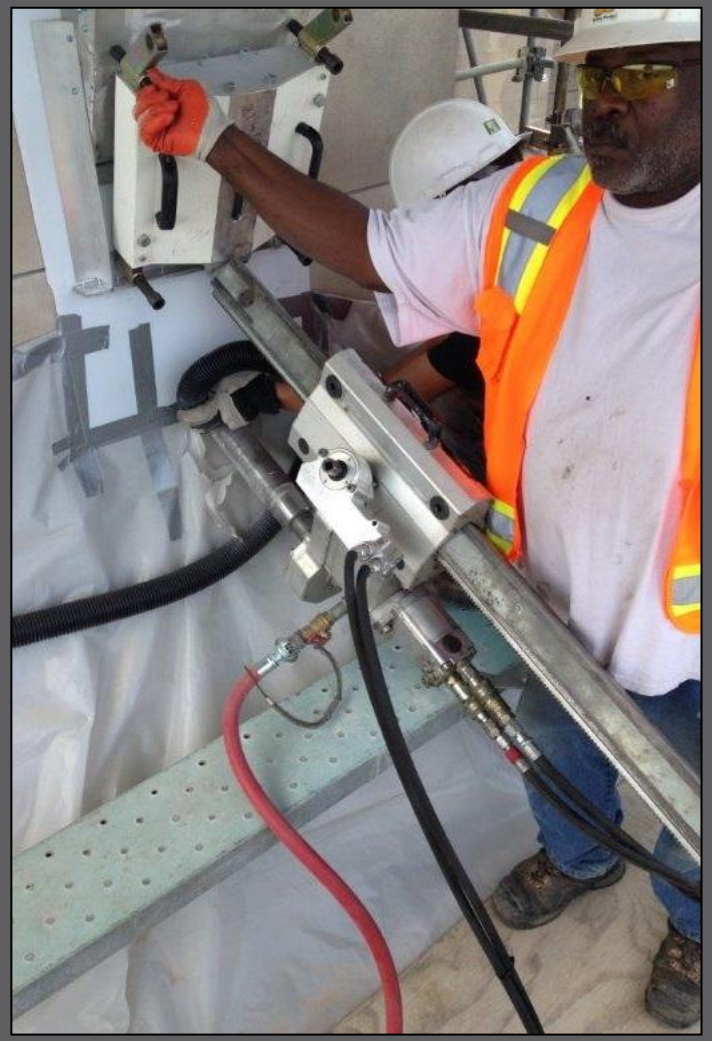


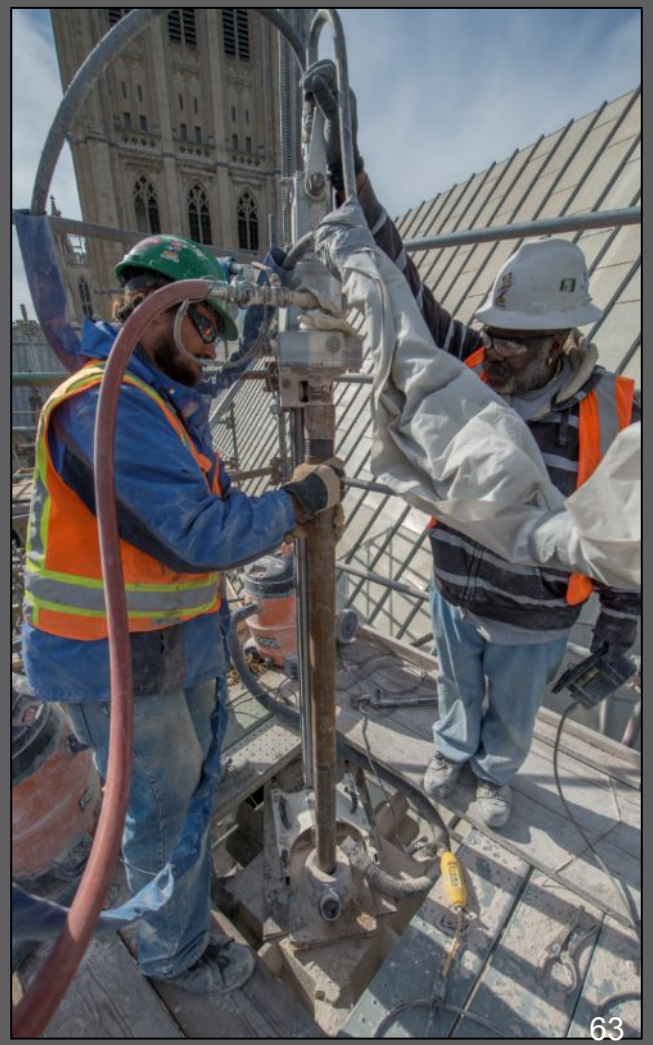
4 TYPICAL LOWER FLIER

SCALE: 1/4" = 1'-0"

So now you've designed something..

Center Coring





Center Coring

Center Coring

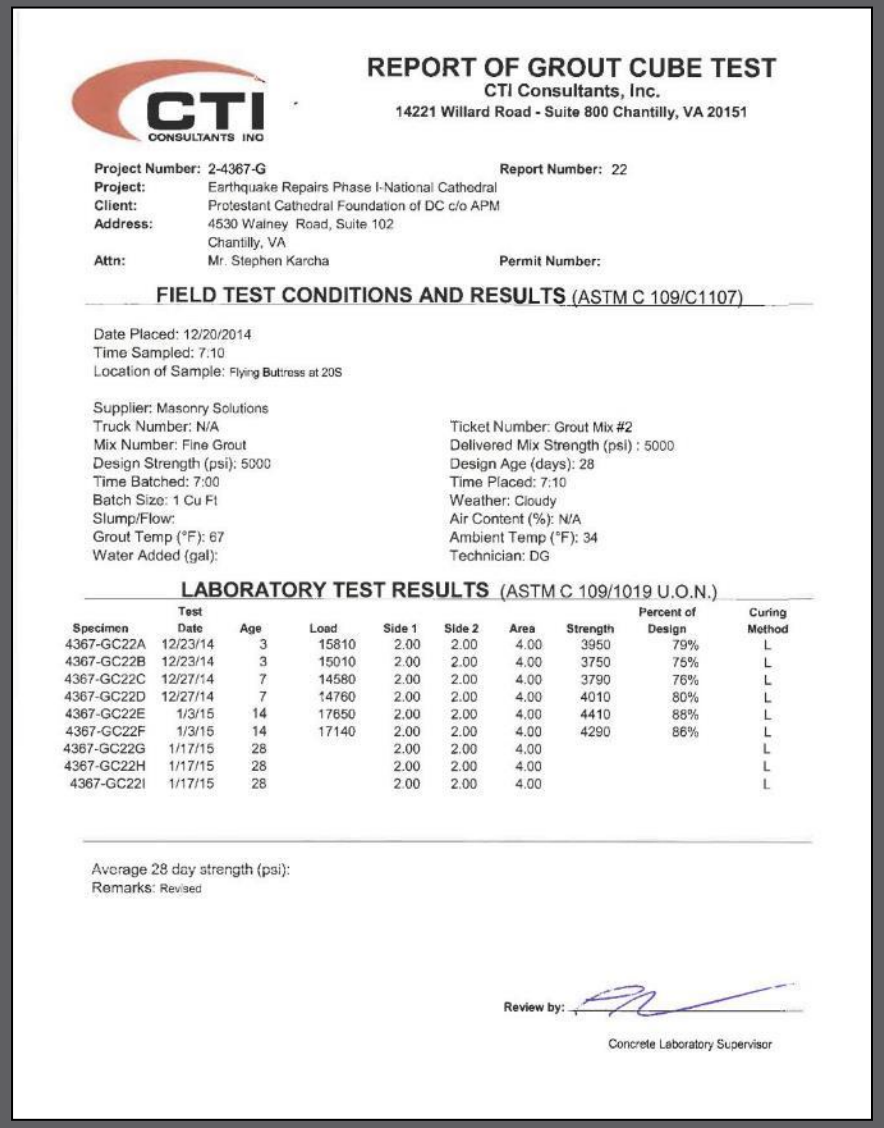
Center Coring

Center Coring

Center Coring

Physical Property Requirements

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



CTI CONSULTANTS INC

REPORT OF GROUT CUBE TEST
CTI Consultants, Inc.
14221 Willard Road - Suite 800 Chantilly, VA 20151

Project Number: 2-4367-G **Report Number:** 22
Project: Earthquake Repairs Phase I-National Cathedral
Client: Protestant Cathedral Foundation of DC c/o APM
Address: 4530 Walney Road, Suite 102
Chantilly, VA
Attn: Mr. Stephen Karcha **Permit Number:**

FIELD TEST CONDITIONS AND RESULTS (ASTM C 109/C1107)

Date Placed: 12/20/2014
Time Sampled: 7:10
Location of Sample: Flying Buttress at 20S

Supplier: Masonry Solutions
Truck Number: N/A
Mix Number: Fine Grout
Design Strength (psi): 5000
Time Batched: 7:00
Batch Size: 1 Cu Ft
Slump/Flow:
Grout Temp (°F): 67
Water Added (gal):

Ticket Number: Grout Mix #2
Delivered Mix Strength (psi) : 5000
Design Age (days): 28
Time Placed: 7:10
Weather: Cloudy
Air Content (%): N/A
Ambient Temp (°F): 34
Technician: DG

LABORATORY TEST RESULTS (ASTM C 109/1019 U.O.N.)

Specimen	Test Date	Age	Load	Side 1	Side 2	Area	Strength	Percent of Design	Curing Method
4367-GC22A	12/23/14	3	15810	2.00	2.00	4.00	3950	79%	L
4367-GC22B	12/23/14	3	15010	2.00	2.00	4.00	3750	75%	L
4367-GC22C	12/27/14	7	14580	2.00	2.00	4.00	3790	76%	L
4367-GC22D	12/27/14	7	14760	2.00	2.00	4.00	4010	80%	L
4367-GC22E	1/3/15	14	17650	2.00	2.00	4.00	4410	88%	L
4367-GC22F	1/3/15	14	17140	2.00	2.00	4.00	4290	86%	L
4367-GC22G	1/17/15	28		2.00	2.00	4.00			L
4367-GC22H	1/17/15	28		2.00	2.00	4.00			L
4367-GC22I	1/17/15	28		2.00	2.00	4.00			L

Average 28 day strength (psi):
Remarks: Revised

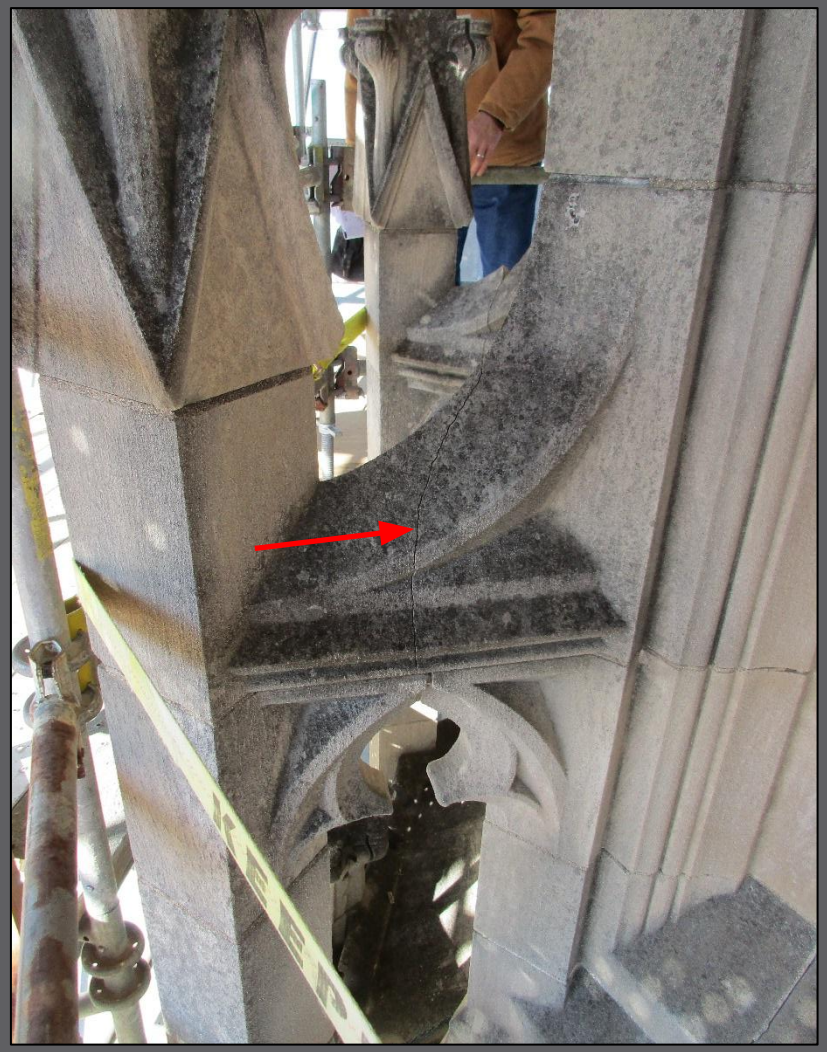
Review by:
Concrete Laboratory Supervisor

Center Coring Challenges

Grout Flow/Control

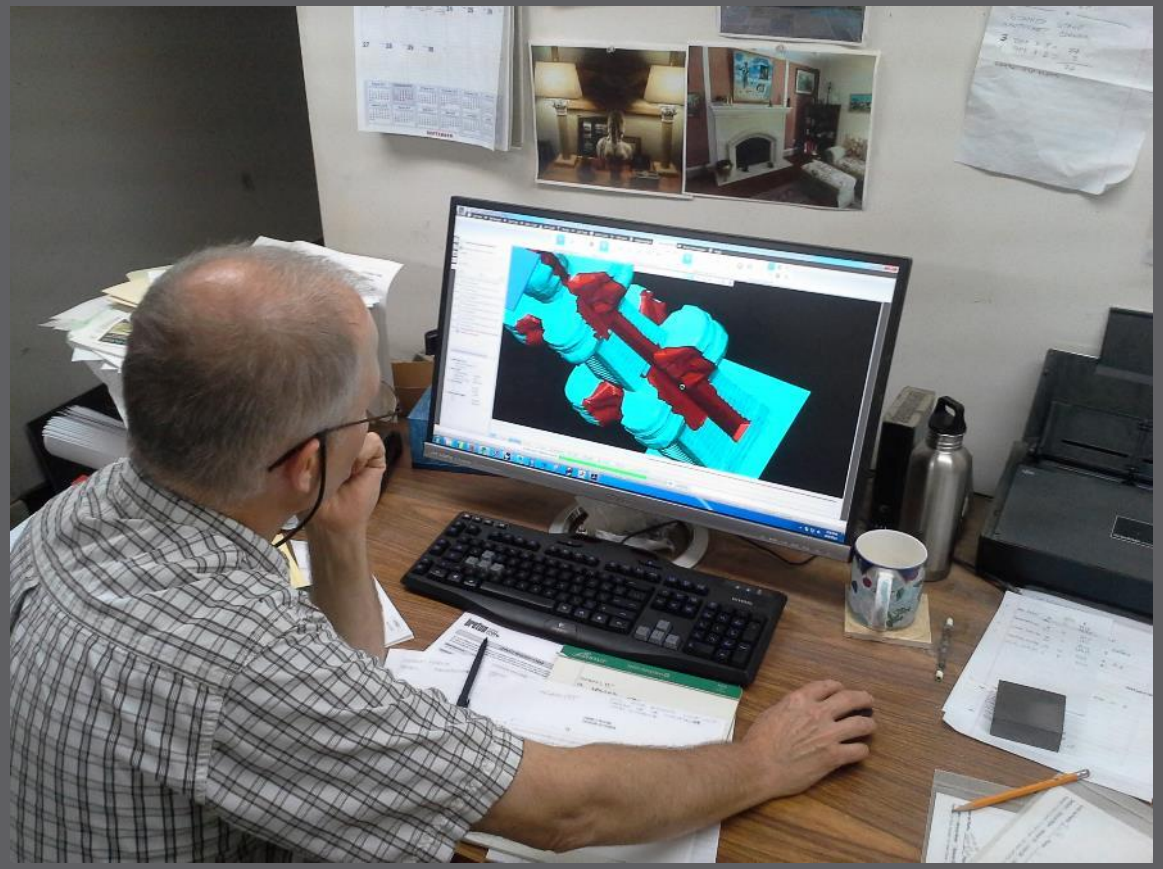
Stone Restoration

North Transept Turret



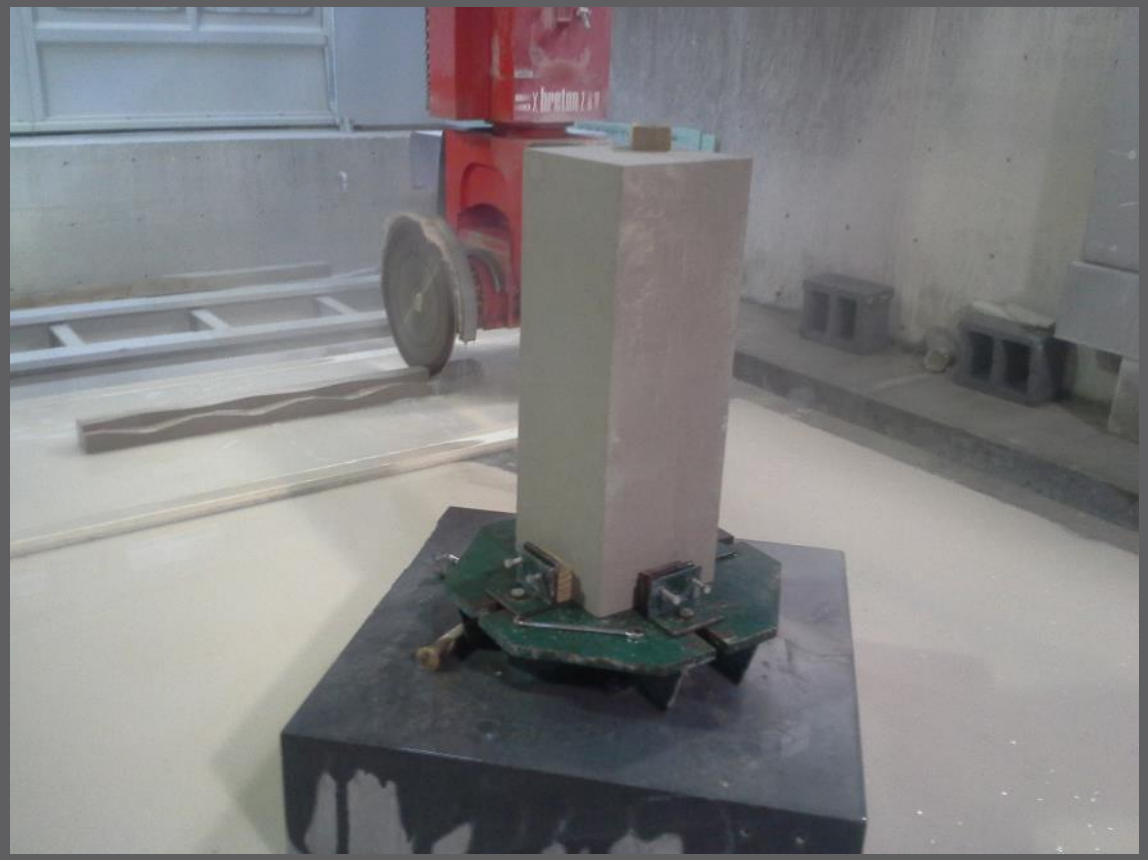
Stone Restoration

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”

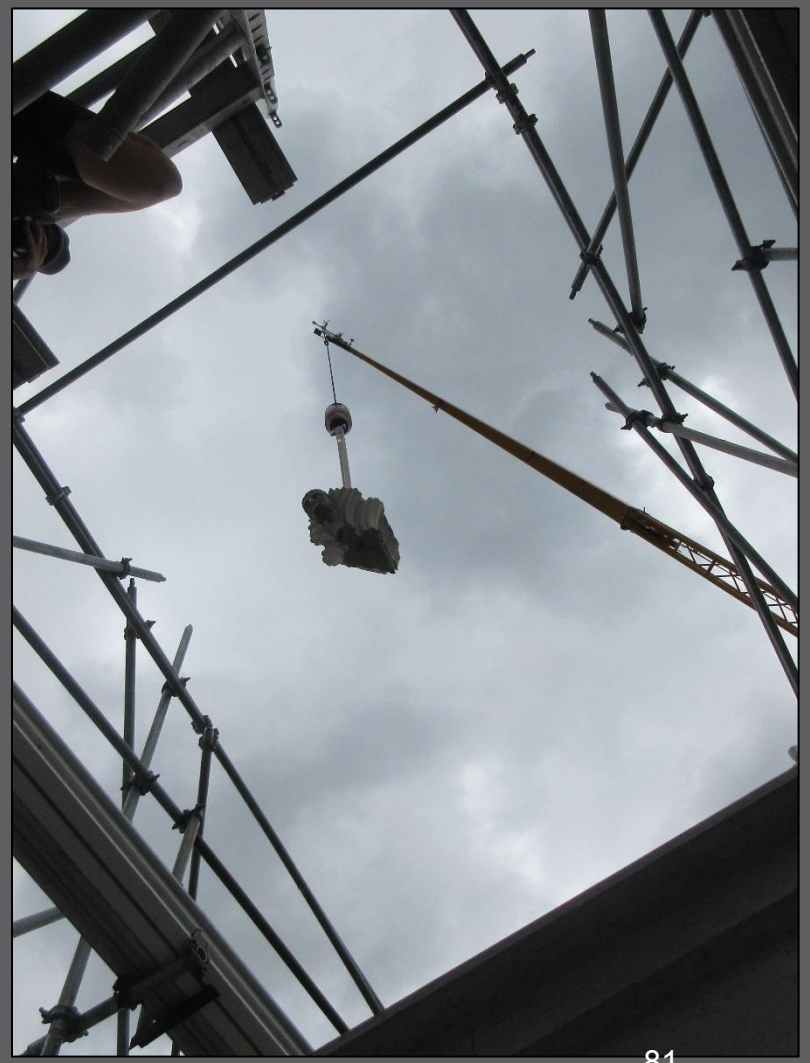
Stone Restoration

“Unforeseen conditions”

Dismantling a Cathedral

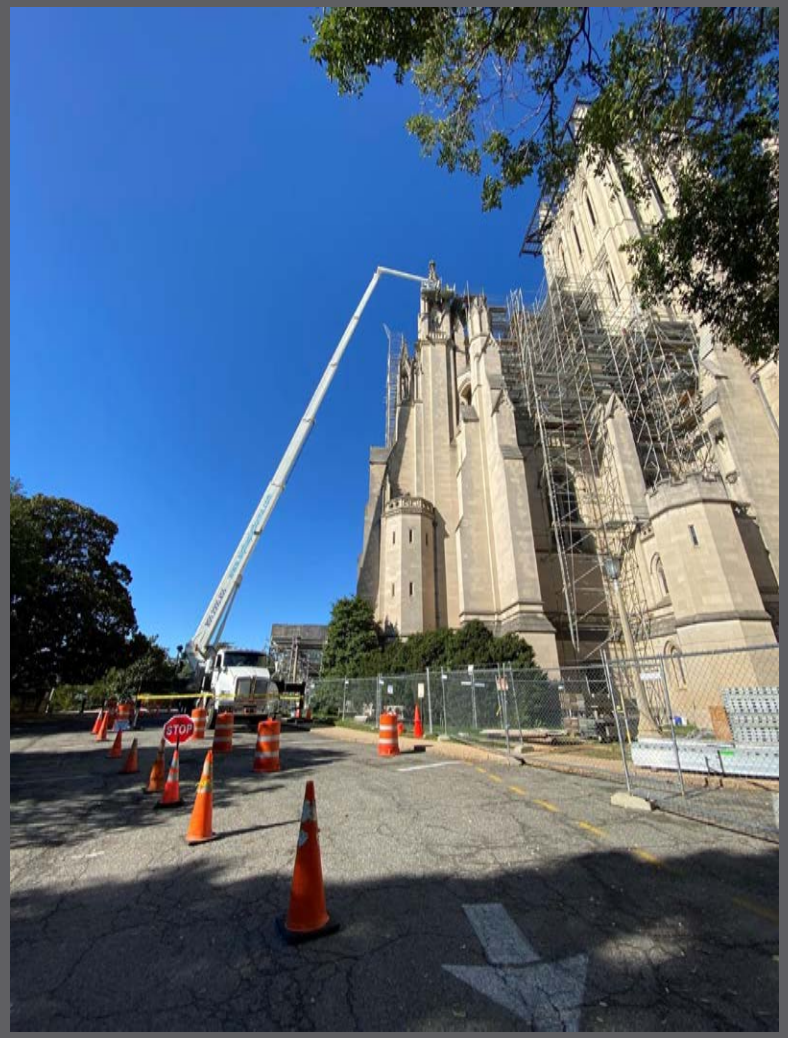
Dismantling a Cathedral

Dismantling a Cathedral



Access

Access



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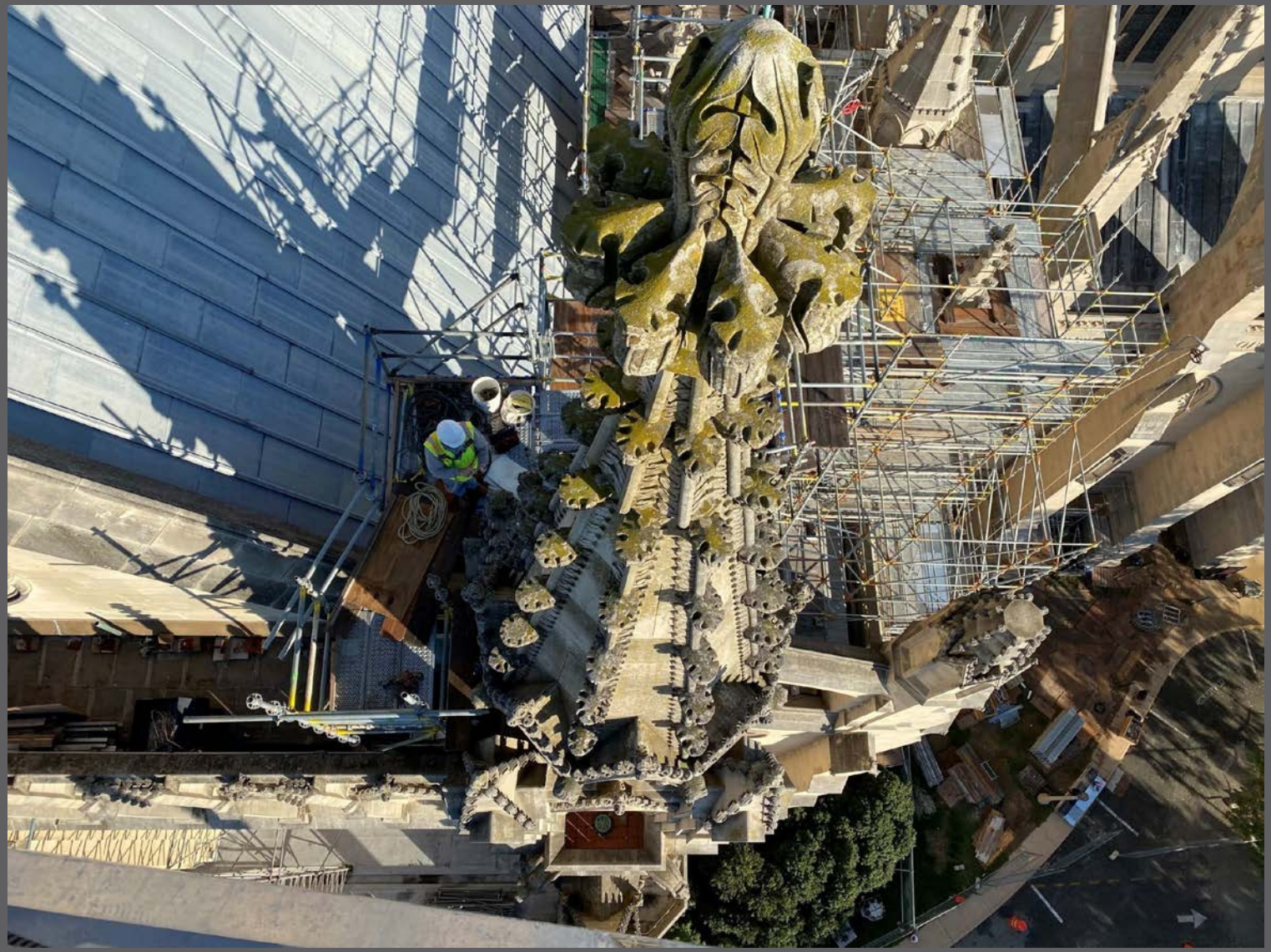
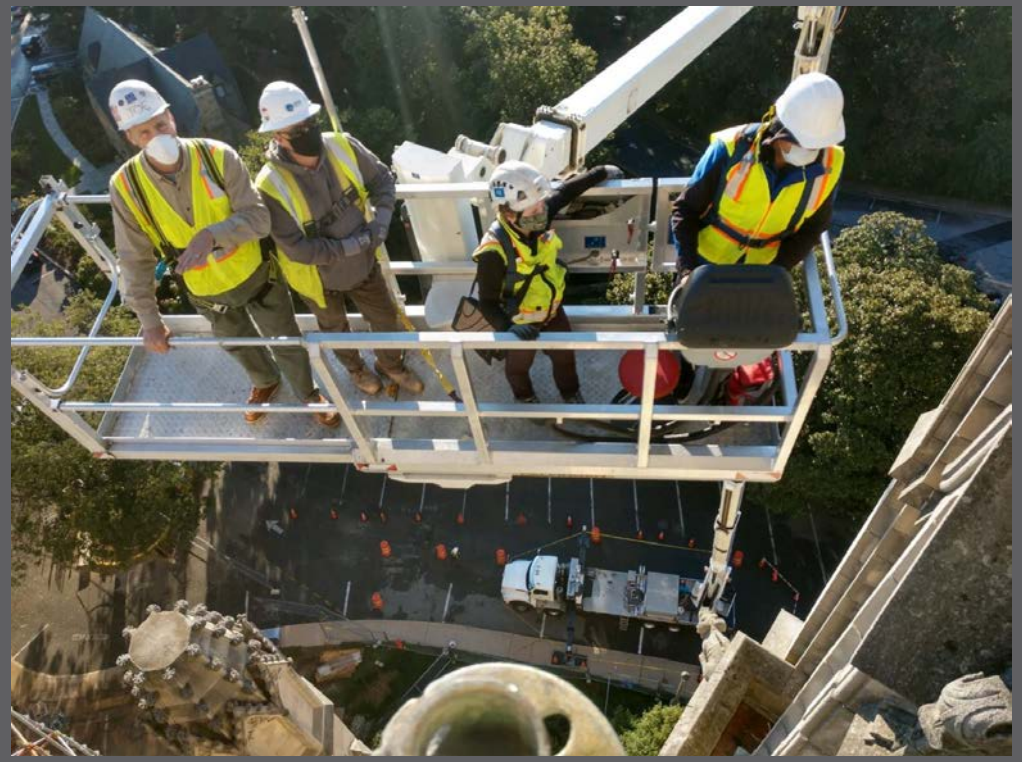


COVID-19

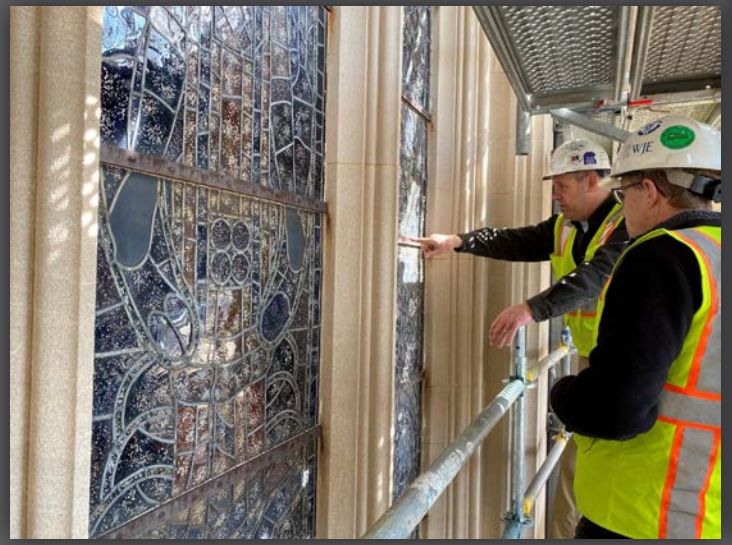
- Social distancing
- Reduced crew size
- Required face coverings

Religion

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



The Team

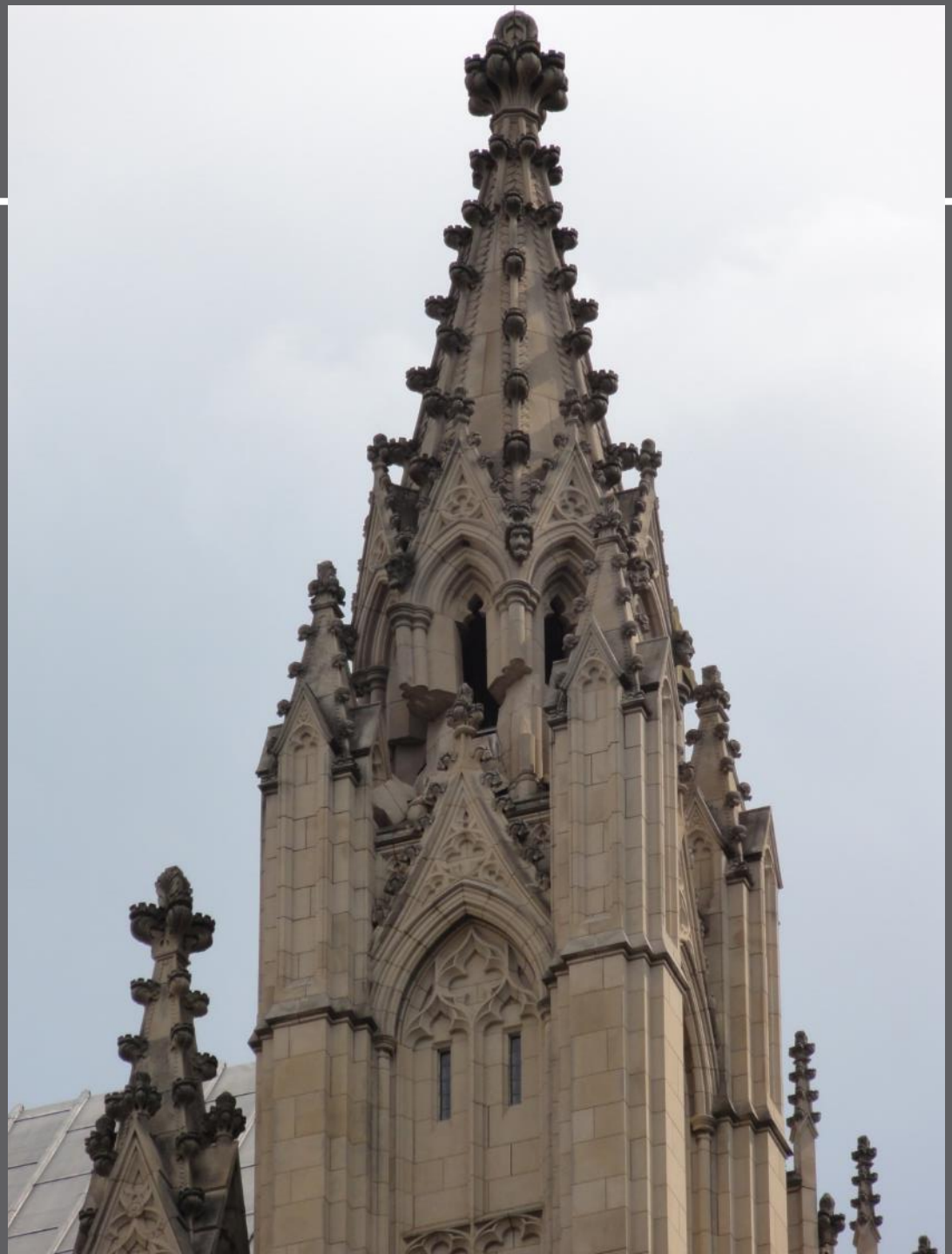


QUESTIONS?

Stabilization Efforts

Scaffolding and Dismantling of South Transept Turret

- Shoring of colonnade



Stabilization Efforts

Dismantling of Central and West Tower Pinnacles