

# The August 23, 2011 Magnitude 5.8 Virginia Earthquake in the Eastern United States - An Engineering Perspective



**J.E. Beavers**

*James E. Beavers Consultants*

**M.R. Eatherton**

*Virginia Tech*

**R.E. Gilsanz**

*Gilsanz Murray Steficek LLP*

**J.M. Ricles & Y.C. Lin**

*Lehigh University*

## **SUMMARY:**

A magnitude 5.8 earthquake occurred in Virginia, U.S. on August 23, 2011 and was the largest magnitude earthquake in Virginia since 1897. The earthquake was centered in Louisa County, Virginia, approximately 130 km South-West (SW) of Washington D.C. Louisa County, a rural area with a population of 33,153, has no hospitals and one high school. The high school and one elementary school had to be closed indefinitely due to structural and nonstructural damage. The earthquake also caused architectural and structural damage in Washington D.C. and was felt by many in New York City and as far north as Canada. A nuclear power plant, located 18 km from the epicenter, was subjected to a peak ground acceleration more than twice its safe shut down earthquake value, but only suffered minor damage to noncritical facilities and was safely shut down during the earthquake.

*Keywords: earthquake reconnaissance, seismic damage, masonry, nuclear, investigation*

## **1. INTRODUCTION**

A magnitude 5.8 earthquake occurred in Louisa County, Virginia at 1:51 p.m., Tuesday, August 23, 2011. The earthquake resulted in a Modified Mercalli Intensity of VII around the epicenter (USGS 2012a) and was the largest earthquake to occur in the state since the 1897 Giles County earthquake.

There were no reported fatalities and only a small number of injuries associated with the earthquake. However, the damages associated with the earthquake have been estimated to be between \$200 million and \$300 million (Morello and Wiggins 2011). Less than \$100 million was insured. Among the buildings damaged, were several iconic structures in the Washington D.C. area including the National Cathedral, Smithsonian Institute, and Washington Monument. Further exacerbating the effects of the earthquake, Hurricane Irene hit Virginia and the Washington D.C area on August 27<sup>th</sup>, just four days after the earthquake.

There are several reasons why the 2011 Virginia Earthquake provides important lessons for the earthquake engineering community on the East Coast of the United States. Sizable earthquakes are not common on the east coast, but have been shown historically to be possible. Although this earthquake was centered in a rural part of Virginia, the next East Coast U.S. earthquake could occur in a more densely populated area. The lessons learned about the vulnerabilities of the existing buildings stock, earthquake preparedness, and types of damage can be applicable to many areas on the east coast.

The authors participated in reconnaissance after the earthquake in the following days and months as part of an Earthquake Engineering Research Institute (EERI) Reconnaissance Team. This paper starts with a discussion of the seismology of Eastern U.S. and characteristics of the 2011 Virginia earthquake. The examination of damage is split into the epicentral area and the Washington D.C. area. Lastly, the lessons that may be learned from this earthquake are drawn.

## 2. SEISMOLOGY AND EARTHQUAKE CHARACTERISTICS

### 2.1. Regional Seismicity

The tectonic stresses in the Eastern Coast of the United States consist of primarily compressive stresses oriented perpendicular to the Appalachian Fold Belt (Zobach and Zobach 1980). These compressive stresses are associated with the same stress field that led to the formation of the Appalachian Mountains 300 to 400 million years ago. The stress field, the Appalachian Mountains, and the Appalachian Fold Belt are shown on Figure 2 as adapted from Zobach and Zobach (1980).

The compressive tectonic stresses in the eastern and central United States are responsible for several seismic areas capable of producing moderate to severe earthquakes. Figure 2.2a shows the seismic hazard in the central and eastern United States. Several large magnitude earthquakes have occurred in this part of the United States in the past two centuries. An earthquake estimated to be M7.3 occurred in Charleston, South Carolina in 1886. A series of four earthquakes hit the New Madrid seismic zone between December 16, 1811 and February 7, 1812. These earthquakes were estimated to be between magnitude 7.0 and 8.0. The largest historical earthquake to occur in Virginia was the Giles County Earthquake of 1897 which was estimated to be M5.9. Three distinct seismic zones have been identified along the line of the Appalachian mountains including the Eastern Tennessee Seismic Zone, Giles County Seismic Zone, and the Central Virginia Seismic Zone (CVSZ) as shown in Figure 2.2b. The August 23, 2011 Virginia Earthquake occurred in the CVSZ, approximately 255 km north-west of the 1897 Giles County Earthquake.

### 2.2. Characteristics of the 2011 Virginia Earthquake

The August 23, 2011 Virginia Earthquake was felt as far south as Georgia and as far north as Canada. Intraplate faults such as those found in the central and eastern United States transmit ground motions much farther than interpolate faults such as those found on the west coast of the United States. As a result, the damage is also more widespread. For example, the New Madrid earthquakes caused damage

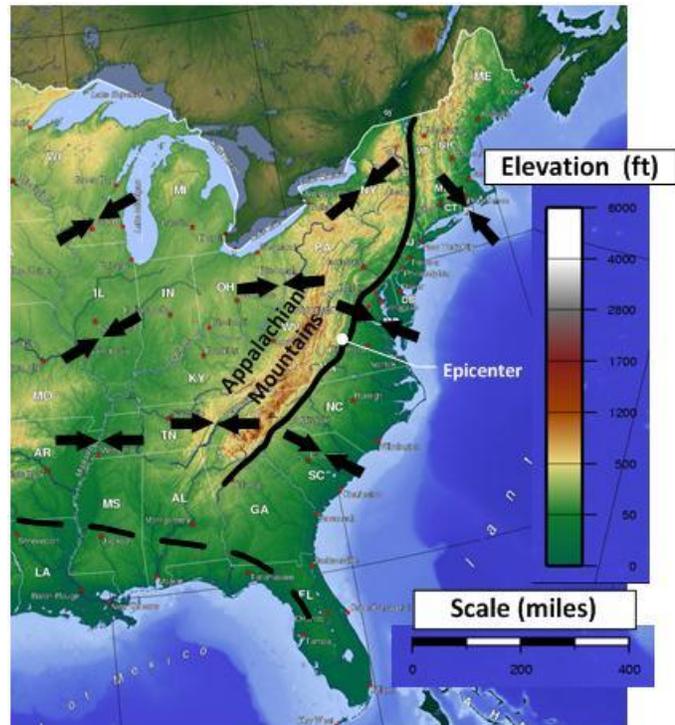
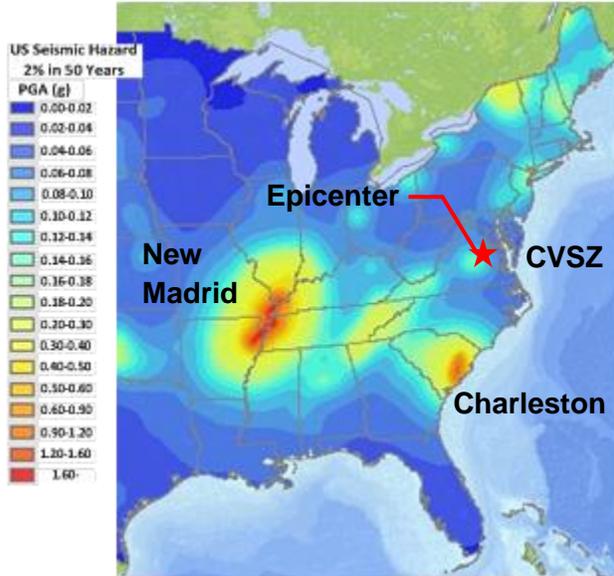
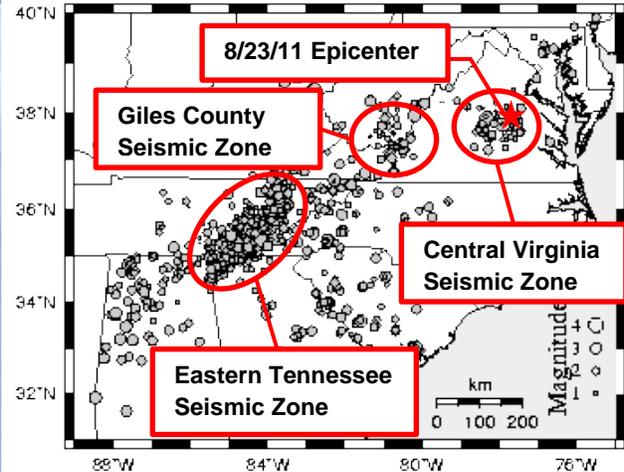


Figure 2.1 - Compression Stresses in U.S. East Coast Adapted from Zobach and Zobach (1980), Topographic map from [http://en.wikipedia.org/wiki/File:USA\\_topo\\_en.jpg](http://en.wikipedia.org/wiki/File:USA_topo_en.jpg)

over an area of 600,000 square kilometers (USGS, 2012b). Figure 2.33a shows the area of the United States that felt the 2011 Virginia Earthquake, and Figure 2.3b shows the areas that experienced damage. The maximum intensity was VII on the Modified Mercalli Intensity Scale. Figure 2.3b shows that Washington D.C., which is 125 km from the epicenter, experienced larger intensity than Richmond (70 km from epicenter), or Charlottesville, VA (50 km from epicenter).

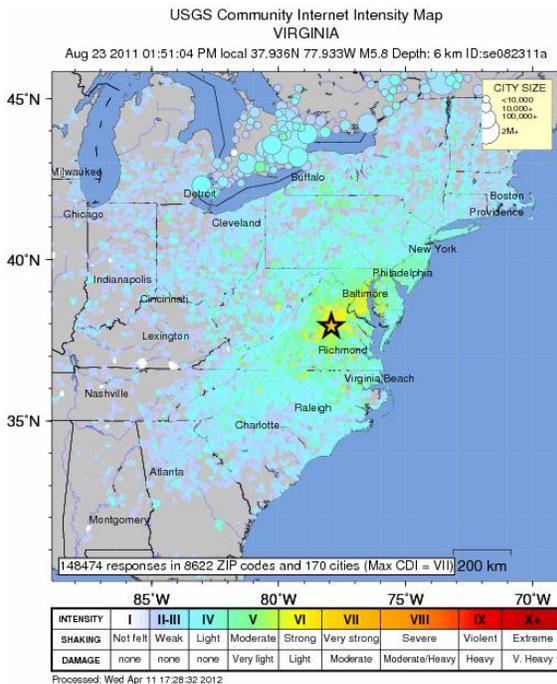


(a) Seismic Hazard Map

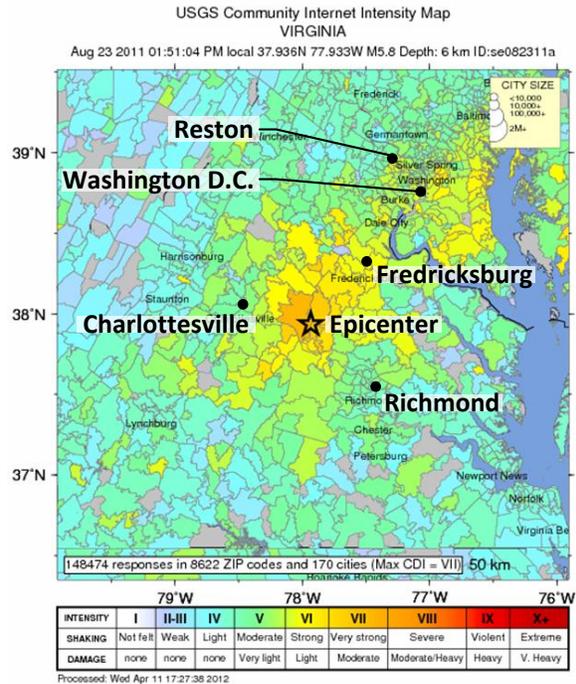


(b) Regional Earthquakes from 1977-1999  
Va Tech Seism. Obser. (VTSO)

Figure 2.2 – Seismicity of Eastern Coast of U.S.



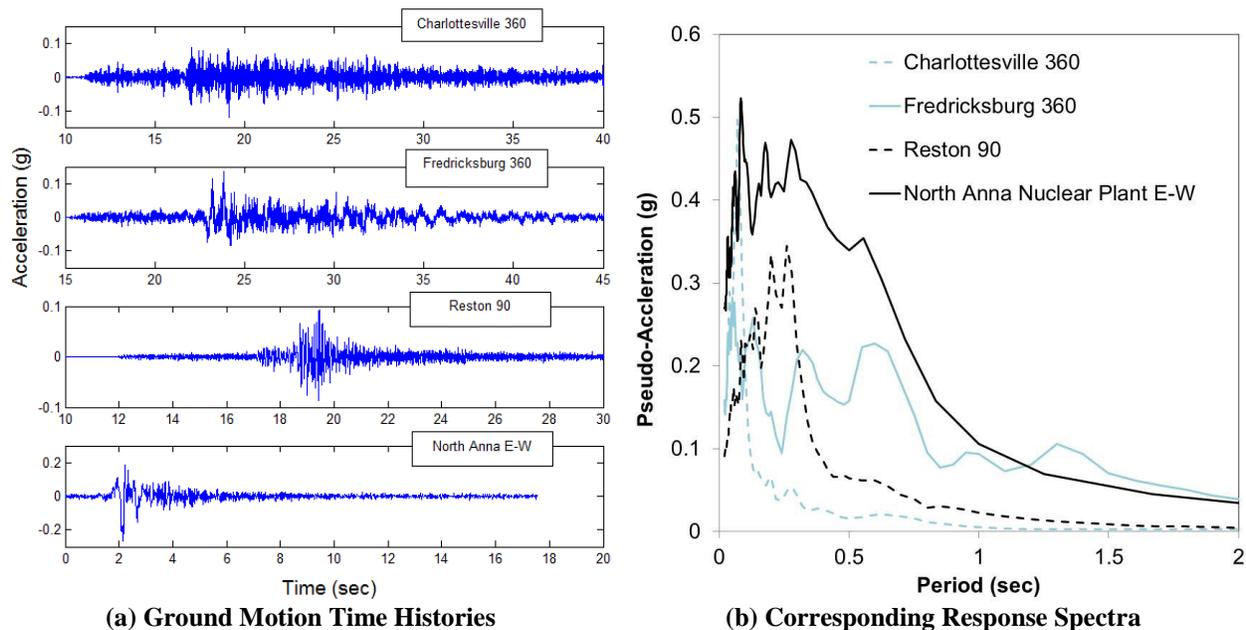
(a) U.S. East Coast Intensity Map



(b) Regional Intensity Map

Figure 2.3 – Modified Mercalli Intensity Due to the August 23, 2011 Virginia Earthquake

There were only a few ground motions recorded within a short distance to the epicenter. Four such ground motions are shown in Figure a with 5% damped response spectra shown in Figure b. The ground motions were recorded in Charlottesville, Virginia (54 km from epicenter with PGA=0.121g), Fredricksburg, Virginia (58 km from epicenter with PGA=0.135g), Reston, Virginia (122 km from the epicenter with PGA=0.109g), and the North Anna Nuclear Power Plant (18 km from the epicenter with PGA=0.27g). A striking feature of the ground motions is the strong energy content at low periods (high frequencies). This is generally characteristic of ground motions in the Eastern U.S. (GEER 2012).



**Figure 2.4 – Ground Motions Recorded During the August 23, 2011 Virginia Earthquake**

The seismic hazard as mapped by USGS suggested that the maximum expected ground motions due to an earthquake in the CVSZ would be 0.12g on a rock site. The North Anna ground motion, recorded on a rock site, had a PGA of 0.27g. Clearly, the seismic hazard associated with the CVSZ will need to be reconsidered as a result of this earthquake.

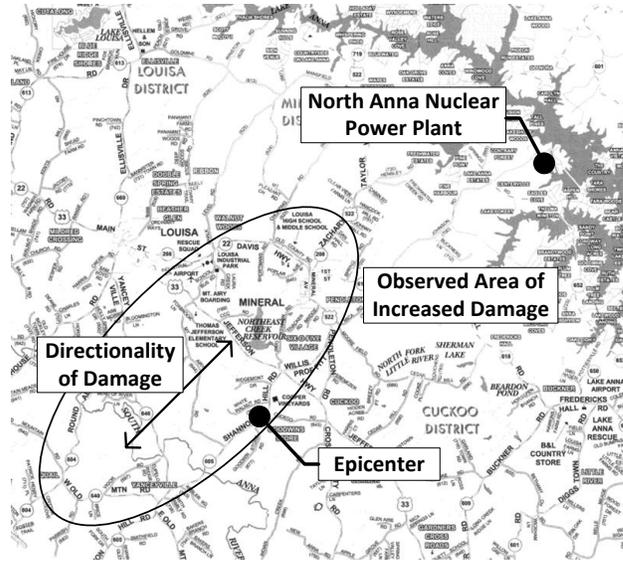
The 2011 Virginia Earthquake occurred in a rural area of Virginia in Louisa County which has a population of 33,153. As a comparison, Washington D.C. is 130 km northwest of the epicenter with a population of approximately 600,000. The population density in Washington, D.C. is approximately two orders of magnitude denser than Louisa County, i.e., 25 people per sq. km versus 3,500 per sq. km.

### 3. STRUCTURAL AND NONSTRUCTURAL DAMAGE IN THE EPICENTRAL REGION

Since the epicentral region is a rural area, the building stock is mostly one to two story residences, and low rise commercial structures. As mentioned previously, there is a nuclear power plant nearby as shown in Figure 3.1 along with a map of Louisa County. The area around the epicenter with increased damage was oriented along a SW / NE line adjacent to the epicenter. A strong directionality was noted in the damage experienced in several buildings which seemed to correlate with this orientation. A similar band of larger seismic intensity is demonstrated in Figure 2.3b

### 3.1. General Types of Damage

It is well known that URM buildings do not perform well during earthquakes. The 2011 Virginia Earthquake highlighted the fact that although URM buildings were no longer built in California after the 1933 and California enacted laws requiring retrofit of URM buildings in 1986, that in the central and eastern United States, URM buildings are not uncommon. Many commercial buildings in downtown Mineral, Virginia have URM storefronts and parapets that were damaged during the 2011 Virginia Earthquake. Two notable historic URM buildings in Louisa County were severely damaged including the Gilboa Christian Church (Figure 3.2a) which was built in 1857, and the Cuckoo House (Figure 3.2b) built in 1819. Initial estimates for repair costs are reported to be \$500,000 for the Gilboa Church as reported on their website. There were also numerous examples of collapsed URM chimneys throughout the epicentral region.



**Figure 3.1 Map of Epicentral Regions with Location of Increased Damage**



**a) Damage to Historic Church**



**b) Damage to Chimneys and Gable of Historic Home**

**Figure 3.2 – Examples of Damage to Unreinforced Masonry Buildings in the Epicentral Region**

Besides damage to URM structures, there was damage to many other types of structures as well. In the region marked on Figure 3.1 as having increased damage, there were many instances of failed brick veneer. Types of brick veneer ties that failed varied widely, from 16d nails driven into straight sheathing and set in mortar joints, to corrugated metal clips that were badly corroded in some cases, and failures in brick veneer that appeared to have been built in the past decade or two. 3.3a shows one example of failed brick veneer.

Other types of damage experienced in the epicentral region included cracked and shifted foundation walls (e.g. Figure 3.3b), collapsed carports (e.g. Figure 3.4), cracked infill walls, damaged hanging ceilings, and other nonstructural damage.



**Figure 3.3 – Examples of Damage to Residences in Epicentral Region**

### 3.2. Performance of Schools

There are two middle schools and one high school in Louisa County. There was enough damage to one of the middle schools and the high school to require them to be shut down indefinitely. The Jefferson Middle School has steel roof joists bearing on masonry exterior walls. Even if lower CMU portions of the wall have reinforcing, the top of the walls were infilled with clay bricks above the ceiling line. Walls perpendicular to the roof framing were generally not well anchored into the roof structure and there were instances of fallen brick and masonry from the top of a wall. One wing of the structure experienced outward bowing of the bearing wall. As shown in Figure 3.5a, the exterior wall developed a hinge at the mortar line just above the window. The wall experienced residual displacement that was noticeable from the interior and exterior of the building.

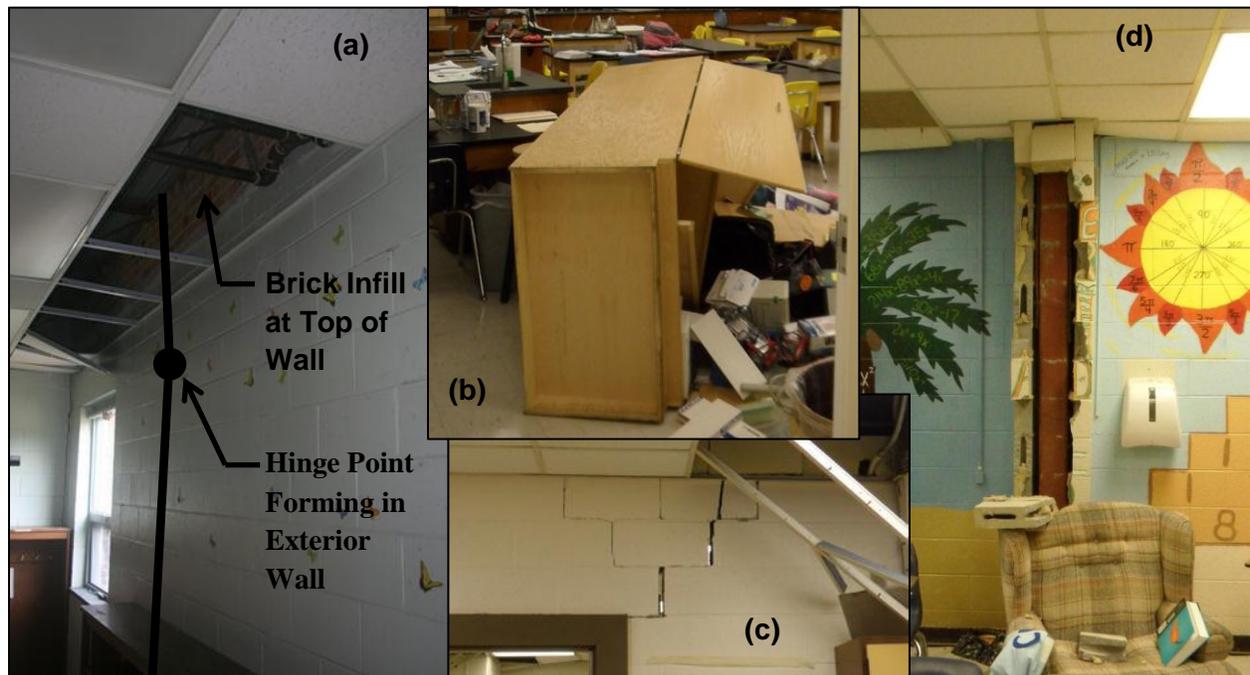


**Figure 3.4 – Collapsed Carport in Epicentral Region**

The Louisa County High School had steel framing and unreinforced masonry infill. One of the few reported injuries occurred at the high school due to falling contents such as shown in Figure 3.5b. Similar damage as described above was observed for the unreinforced CMU infill walls such as cracking (shown in Figure 3.5c) and falling bricks. There was evidence of considerable movement of the steel framing relative to the CMU infill as the CMU surrounding the steel columns was commonly cracked and in some cases collapsed (Figure 3.5d). It was impossible for the Reconnaissance team to fully assess the damage to these buildings, but the estimate for repair of the high school was \$43 million (Kumar 2012).

It was reported by people present in the Louisa County High School that during the earthquake the fire alarms were sounded. It was conjectured that this may have been associated with a loss of water pressure

in the sprinkler system. As a result, occupants of the school began evacuating the building even while the earthquake was still ongoing. A small percentage of the occupants sought cover during the earthquake. In general, the majority of people in Virginia and Washington D.C. interviewed did not understand proper response during an earthquake.



**Figure 3.5 - Performance of Schools in the Epicentral Region (a) Jefferson Middle School, (b) Falling Contents at Louisa High School, (c) Unreinforced CMU Infill walls at Louisa High school, and (d) Differential Motion of Steel framing Relative to CMU Infill at Louisa High School. [Some photos Courtesy of R. Green]**

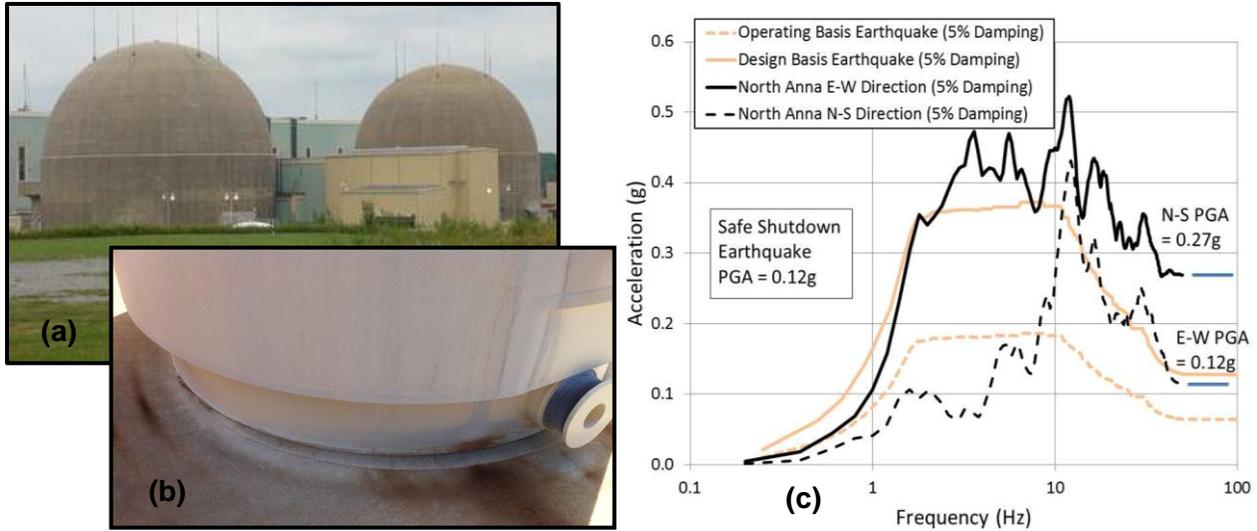
### 3.3 Performance of the North Anna Nuclear Power Plant

As shown in Figure 3.1, the North Anna Nuclear Power Plant was 18 km from the epicenter and in line with the directionality of the observed damage. The reactors underwent a safe shutdown procedure following the earthquake. The reactors' containment structures, Figure 3.6a, were designed to remain elastic for a peak ground acceleration of 0.12g and as shown in

Figure 3.6c, the measured PGA at the site was 0.27g. However, detailed inspections by Dominion Power, and Nuclear Regulatory Commission inspectors revealed no safety related damage (Bacque and Martz 2011, Dominion Power 2011). In November, the North Anna Nuclear Power Plant was cleared by the Nuclear Regulatory Commission to restart their reactors (Bacque and Martz 2011).

Two weeks after the earthquake, parts of the EERI and GEER reconnaissance teams were allowed to visit the North Anna Plant and investigate some of the noncritical structures. Minor damage was observed in a few of the noncritical facilities such as hairline diagonal cracking in some CMU walls. Cranes were functional in tall steel space frame buildings on the site implying negligible residual deformations. Nor was there any evidence of sliding of large water tanks. Twenty seven large storage casks, each weighing 520 kN were found to have shifted on their concrete slab. As shown in

Figure 3.6b, these casks used for dry storage of spent fuel rods slid as much as 114mm.



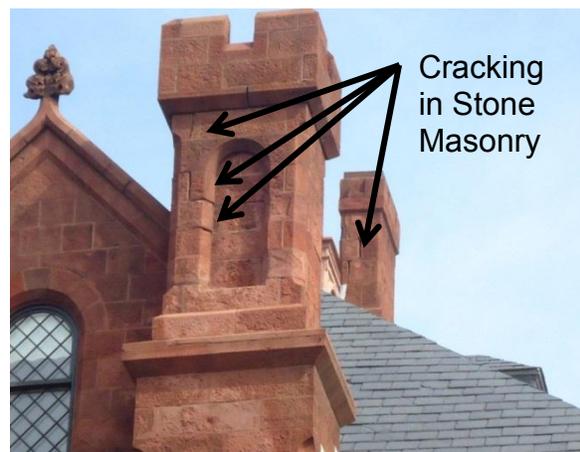
**Figure 3.6 – (a) North Anna Nuclear Power Plant, (b) Shifted Dry Storage Casks and (c) Recorded Ground Motions**

#### 4. DAMAGE IN THE WASHINGTON, D.C. AREA

Reconnaissance of damage in the Washington D.C. is important because there is large population and density of population, the Modified Mercalli Intensity was larger in Washington D.C. than in any of the other cities in the region, and the city is also the home to many important buildings related to national government, federal administration, international embassies, and museums.

Members of this reconnaissance team went to Washington D.C. along with part of the GEER Team on September 8 and 9 a little over two weeks after the earthquake. The investigation centered on the Smithsonian Institute. The Smithsonian headquarters building known as the Castle, a historic building built in the mid-1800s, had experienced considerable architectural damage and some structural damage. In addition, the Pods, where the Smithsonian stores their non-displayed items experienced damage.

The Castle is a historic building built in the mid-1850s of unreinforced masonry and stone as shown in Figure 4.1. Large differential movement of stone elements can be seen in Figure 4.1. The Castle also experienced some other architectural damage of plaster cracking, and dislodged windows. The Castle was evacuated following the earthquake and was not reopened until complete safety inspections had occurred by the Smithsonian Institutes' Engineer of Record. Employees were allowed to return to work the following Monday, six days after the earthquake.

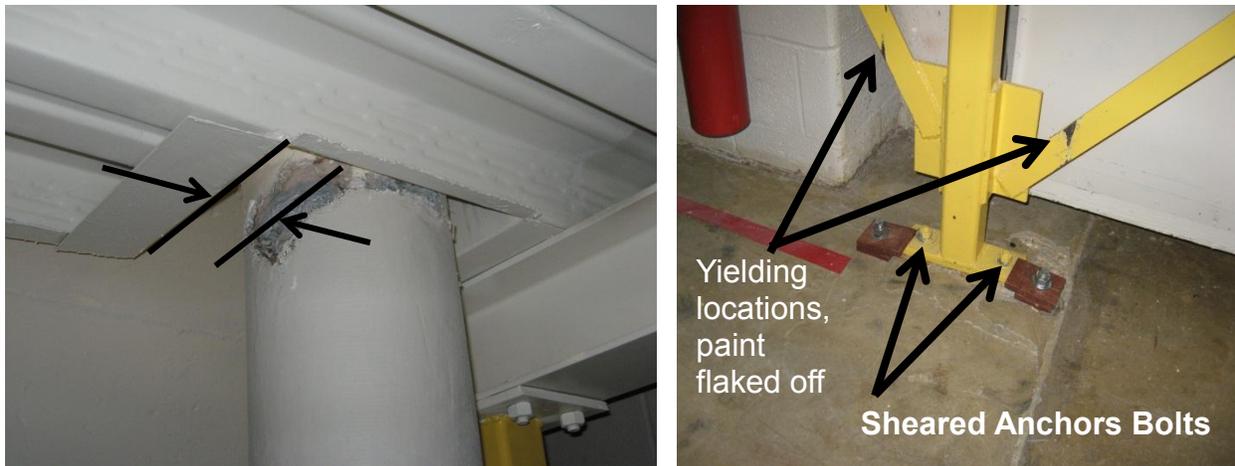


**Figure 4.1 - Cracked Chimneys at the Smithsonian Institute Castle**

The Pods are warehouses where the non-displayed artifacts are stored. The Pods are pre-cast concrete buildings three stories tall with an interior steel frame building connected to the pre-

cast concrete building only at the foundation, this construction can be summarized as a building within a building. The interior steel frame buildings are constructed of box columns with cross-bracing to support lateral loads. The Pods are warehouses where the non-displayed artifacts are stored. The Pods are pre-cast concrete buildings three stories tall with an interior steel frame building connected to the pre-cast concrete building only at the foundation, this construction can be summarized as a building within a building. The interior steel frame buildings are constructed of box columns with cross-bracing to support lateral loads. The floors are typical decking consisting of about four inches of concrete. The non-displayed exhibits are stored on all three floors in all four Pods. On inspection of the Pods it was evident that they each experience loads significantly beyond their design bases. However, when the Pods were built in the mid-1980s, there were no seismic design requirements in the Washington, D.C. area and the response of the steel frames and precast concrete buildings showed their weakness through differential displacements.

For example, at one location one can see as much as 15 cm of differential displacement as shown in Figure 4.2a. In addition, the lateral cross bracing between the steel columns yielded on all three floors and many steel column anchor bolts were sheared off as shown in Figure 4.2b.



a) Banging between floor and fire protection and piping, approximately 15 cm or more of movement      b) Anchor Bolt Shear and Yielding

**Figure 4.2 – Typical Damage to Smithsonian Institute Pods**

In addition to the Smithsonian institute, other iconic structures in the Washington D.C. area experienced damage. The Washington Monument underwent severe shaking as caught on surveillance video. Cracks formed in the monument, and a debris field was developed inside the structure and around the base of the structure (Ruane 2011). The Washington Monument has been closed since the earthquake pending repair which is estimated to cost \$15 million (Zongker 2012). The National Cathedral, which has many intricately carved stone elements, experienced significant architectural damage during the earthquake. The repair costs are estimated to be \$20 million (Markoe 2012).

## 5. CONCLUSIONS

The August 23, 2011 Virginia Earthquake should be a wake-up call for the Central and Eastern U.S. Although this earthquake was centered in a rural part of Virginia, it still caused between \$200 million and \$300 million of damage. The next large earthquake on the East Coast of the U.S. could occur in a more populous area, in which case the result could be much more severe damages, injuries, and fatalities. Some of the lessons learned from this earthquake that may help prepare for future Central and East Coast U.S. earthquakes include:

- The mapped seismic hazard associated with the Central Virginia Seismic Zone is underestimated. The ground motions recorded from this earthquake exceeded expected maximum ground motions by a factor of two. Furthermore, the low period energy content in East Coast U.S. ground motions may not be captured adequately in current seismic hazard characterization.
- Unreinforced masonry buildings are dangerous in earthquakes. Although this is not a novel observation, it was found that there is a surprising amount of URM in the building stock including store fronts, chimneys, and old URM structures. Although URM structures in California have been required to be retrofitted, no such laws have been enacted on the East Coast.
- Schools in the epicentral area were found to be more susceptible to damage than typical buildings. It could be argued that school structures should be designed to satisfy a higher seismic performance standard than typical buildings instead of a lower standard.
- The recorded PGA at the North Anna nuclear power plant exceeded the design values by a factor of two. However, the robustness of design was demonstrated as negligible damage was found after the earthquake.
- Some of our nation's most iconic structures were found to be the most susceptible to damage since they are largely unreinforced masonry. Rebuilding of these structures should include seismic retrofit to protect against damage and collapse in the next earthquake.

## ACKNOWLEDGMENTS

The authors would like to thank the Earthquake Engineering Research Institute (EERI) for funding and organizing the reconnaissance trips. The authors would also like to thank the members of the Geotechnical Extreme Events Reconnaissance (GEER) team for their cooperation and help in this investigation.

## REFERENCES

- Bacque, P. and Martz, M. (2011) "North Anna Nuclear Reactors Coming Back Online" Richmond Times Dispatch Published November 12, 2011, <http://www2.timesdispatch.com/>
- Dominion Power, (2011). "Overview of 08/23/11 Earthquake Response and Restart Readiness Demonstration Plan." Presentation to the Nuclear Regulatory Commission on September 8, 2011.
- GEER (Geotechnical Extreme Events Reconnaissance) Team (2012). *Geotechnical Reconnaissance of the 2011 Central Virginia Earthquake: Report of the National Science Foundation-Sponsored GEER Team*. J. R. Martin, (editor).
- Kumar (2012) "Louisa Recieves \$19 Million for Earthquake-Damaged School" Washington Post, Posted 02/23/2012, [www.washingtonpost.com](http://www.washingtonpost.com)
- Markoe L. (2012) "Washington National Cathedral Repairs are Going Slow, Could Stretch Out a Decade or More" The Huffington Post, [www.huffingtonpost.com](http://www.huffingtonpost.com)
- Ruane, M.E. (2011) "Washington Monument Closed Indefinitely" Washington Post, [www.washingtonpost.com](http://www.washingtonpost.com)
- USGS (2012a) "M5.8 Virginia" <http://earthquake.usgs.gov/earthquakes/dyfi/events/se/082311a/us/index.html> United States Geological Survey
- USGS (2012b) "Historic Earthquakes" <http://earthquake.usgs.gov/earthquakes/states/events/1811-1812.php> United States Geological Survey
- Zobach, M.L. and Zobach, M. (1980) "State of Stress in the Conterminous United States" Journal of Geophysical Research, Vol. 85, Nno. B11, pp. 6113-6156
- Zongker, B. (2012) "Billionaire Donates for Washington Monument Repairs" [www.MSNBC.com](http://www.MSNBC.com)