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A CASE STUDY OF POST-EARTHQUAKE STRUCTURAL ENGINEERING – THE BALTIMORE BASILICA

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ABSTRACT

The response, assessment, and recovery effort as undertaken by Keast & Hood Co. for the Archdiocese of Baltimore provides a case study for post-disaster preservation of historic structures including immediate response, temporary stabilization, and post-response repairs with visually subtle, yet structurally sound, restoration detailing.

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The response, assessment, and recovery effort as undertaken by Keast & Hood Co for the Archdiocese of Baltimore provides a case study for post-disaster preservation of historic structures including immediate response, temporary stabilization, and post-response repairs with visually subtle, yet structurally sound, restoration detailing.

Introduction

As a result of the Mineral, Virginia, earthquake on August 23, 2011 and associated aftershocks, a number of historic masonry structures throughout the Baltimore-Washington area sustained varying degrees of damage. Since the August 2011 earthquake, Keast & Hood Co. (K&H) has had numerous opportunities to provide structural engineering services as part of the post-disaster response, assessment, and recovery of historically sensitive structures. Among the numerous historic structures impacted by the August 2011 earthquake, The Baltimore Basilica sustained significant damage.

Background

Historical Significance

Throughout history, churches have been central to city life. With tall, thin spires intended as landmarks, a church defined a community's identity. Restoration of historic church structures brings cohesion and a sense of identity back to a community. The historic Baltimore Basilica welcomed over 200,000 visitors from across the world within the first year following its 2003-2006 renovation. This renovation included excavation of the undercroft and installation of a new roof.

Officially known as the Basilica of the National Shrine of the Assumption of the Blessed Virgin Mary, and designed by the noted American architect, Benjamin Henry Latrobe, the Baltimore Basilica is a fine example of neoclassical style while conforming to the traditional Latin cross floor plan, marrying a domed space with a longitudinal building axis. Established as the first cathedral in our nation's history following the adoption of the Constitution, the Basilica is a symbol of our nation's independence and an expression of the Catholic Church's new found religious freedom. The walls are seeped with history that stems from the foundation and

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undercroft.

Existing Structure

Constructed between 1806 and 1821, the building is primarily structured from brick masonry bearing walls, piers, barrel vaults, and domes. The exterior facade is clad in granite with Keim-coated inset panels and parapets. The wood-framed roof spans north to south. The front portico is framed with a granite staircase and granite sidewalls. The portico floor is a combination of marble and slate tiles. Eight fluted columns support the entablature and pediment above. The gabled portico roof is framed from wood purlins and iron trusses. Two brick masonry bell towers are found directly behind the portico on the north and south sides of the building.

Engineering Response & Assessment

Immediate Response

Following an immediate emergency response at Saint Patrick's Church in Baltimore, Maryland, K&H performed a whirlwind day of assessments at the request of the Archdiocese of Baltimore (AoB). Foremost among these buildings was the Baltimore Basilica located in downtown Baltimore, Maryland.

Notable damage included visible cracks in the plaster walls, vaults, arches, and domes. K&H judged these plaster cracks were an indicator of underlying brick masonry distress. The immediate response was not intended to document all visible cracks, but to more accurately establish the safety and structural stability of the structure for daily activities. While cracked plaster was observed throughout the Basilica, K&H judged the earthquake had not impaired the structure to the point where life safety was a concern and daily activities could resume. This

Structural Engineering Assessment

Initial Assessment

In the weeks following the Mineral, Va., earthquake, K&H conducted a condition assessment of The Baltimore Basilica to review the existing structure. K&H reviewed the finishes for evidence of distress. A binocular survey was performed from ground level to observe all portions of the façade, interior barrel vaults, and domes to observe previous-noted cracks within the walls, vaults, arches, and domes, and to discern additional areas not as apparent to the naked eye. Digital photographs were used to record existing conditions. No materials were removed for testing.

The Basilica is open daily with public access to the main cathedral and undercrofts below. At the request of the client, K&H's initial assessment was tailored to avoid negatively impacting daily activities and public access to the building. As such, lifts and scaffolding were not utilized to assist with the initial assessment. Additional probes were not implemented to avoid disrupting the overall visual appearance of the Basilica while open for public access.

The following figures highlight select initial observations and recommendations:

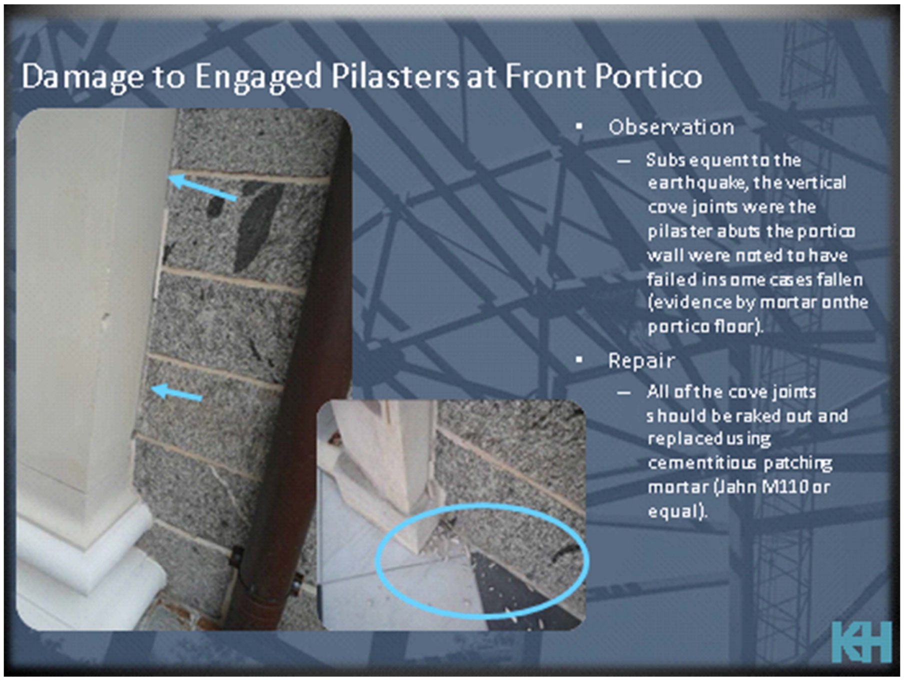

Figure 1. Damage to engaged pilasters at front portico.

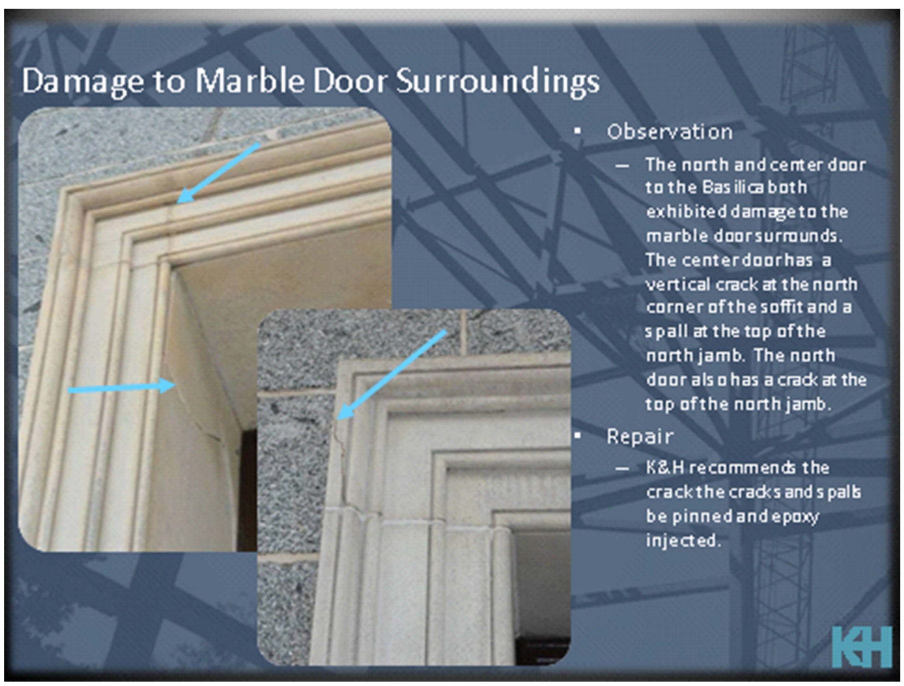

Figure 2. Damage to marble door surroundings.

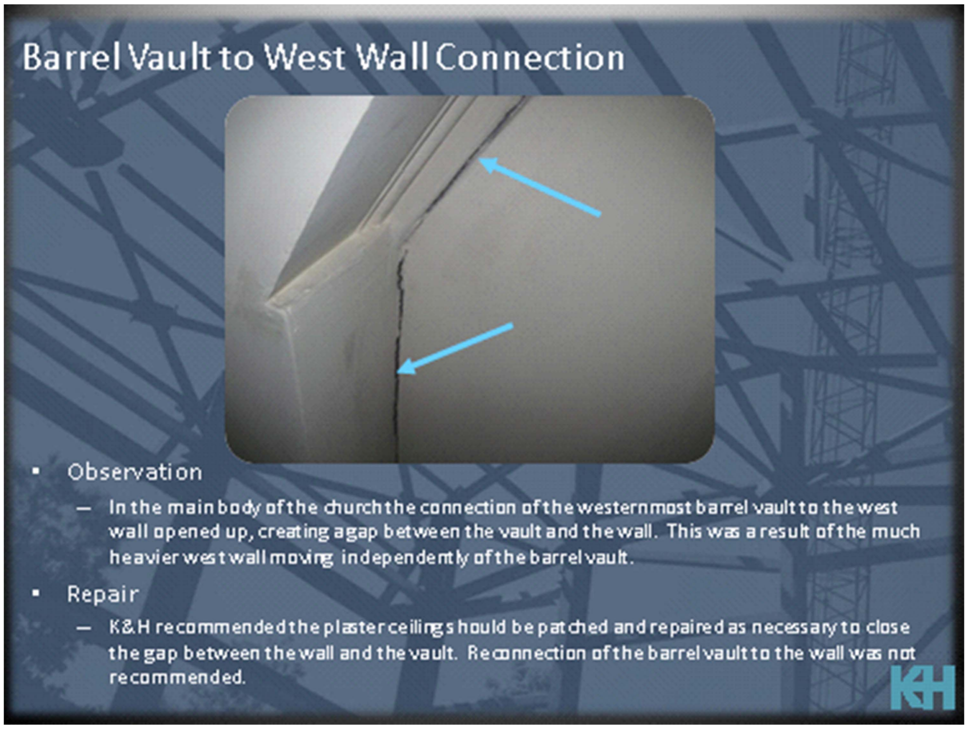

Figure 3. Separation between barrel vault and west wall connection.

Figure 4. Distress at North Bell Tower to West Bell Tower connection.

Figure 5. Radial cracking at bell tower cornices.

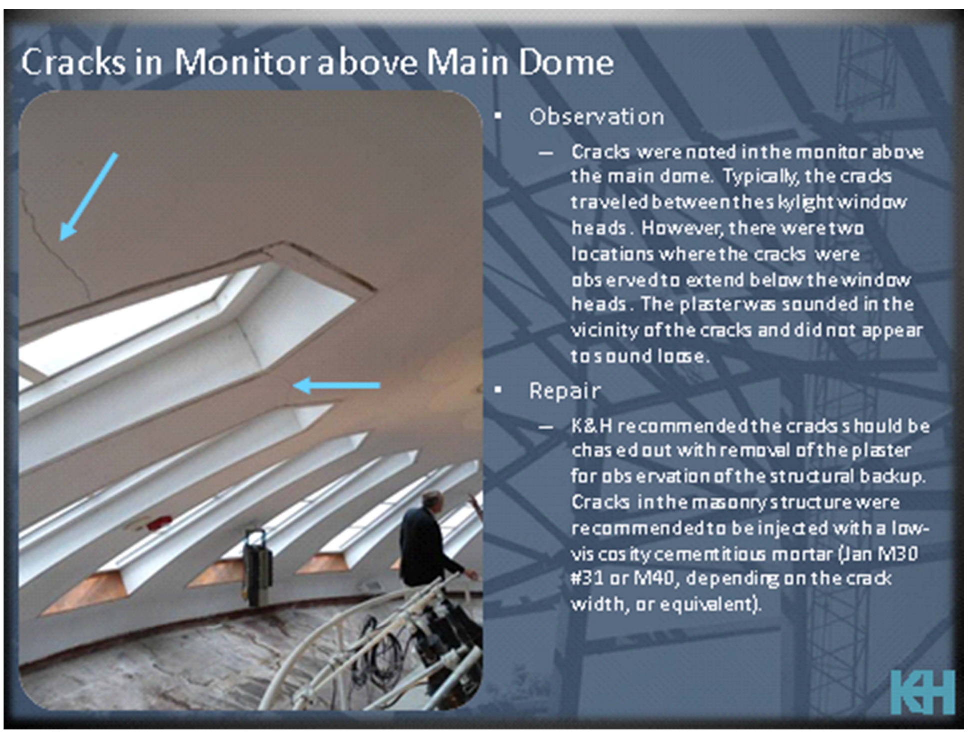

Figure 6. Cracks in monitor above main dome.

Figure 7. Cracks in exterior cornice.

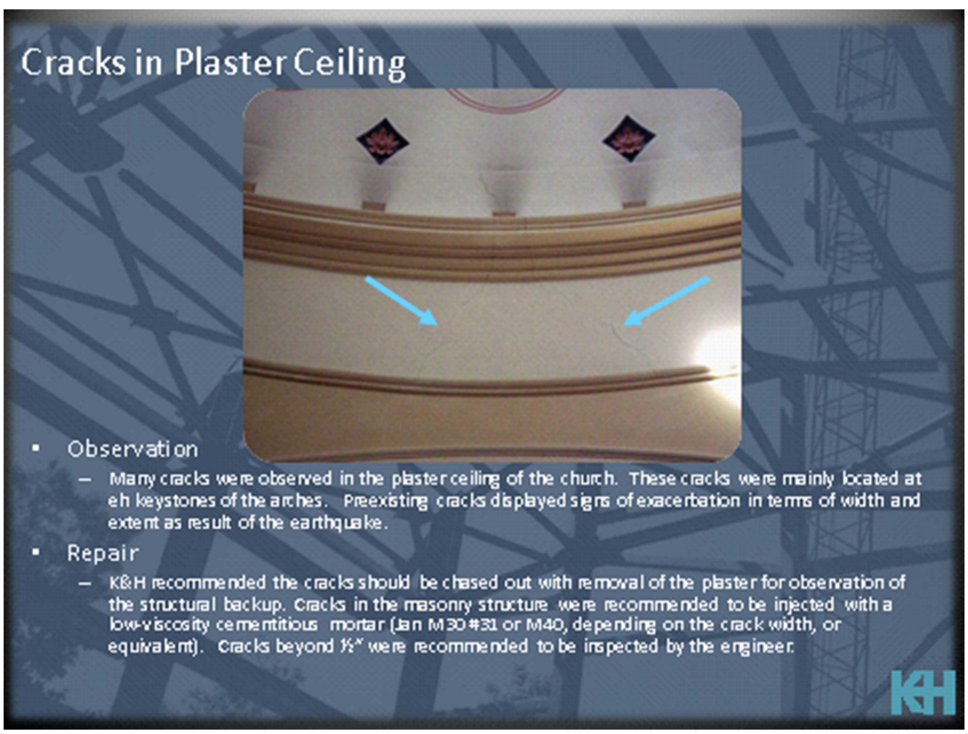

Figure 8. Cracks in plaster ceiling.

Structural Response and Recovery

Construction Schedule Coordination

In response to the initial structural assessment observations and recommendations, the Archdioceses of Baltimore engaged K&H to lead a team of consultants to return the Basilica to its pristine pre-earthquake condition. This process included compilation of construction drawings and specifications for repairs to the historically sensitive structure.

As previously mentioned, additional probes, selective demolition, and removal of finishes were not performed in order to avoid negatively impacting the daily activities of the Basilica. Instead, the design team worked closely with the client and insurance agent to help bridge the gap of uncertainty associated with the lack of additional work prior to the construction process.

The recent 2006 renovation, which restored the Basilica's pristine architectural beauty, included extensive interior plaster, paint, and other non-structural restoration. In light of those recent aesthetic repairs and the limitation restricting additional probes, selective demo, and removal of finishes, K&H and the design team developed a map of structural repairs. Areas of visually apparent cracked plaster were assumed to be indicative of cracked masonry beyond. Construction pricing at these areas was developed to account for both plaster repair and typical masonry crack repairs (crack injection). Figure 9 pictures a reflected ceiling plan indicating areas of cracked masonry requiring repairs. Fig. 9 also illustrates the extent of potentially invasive repairs required throughout the Basilica.

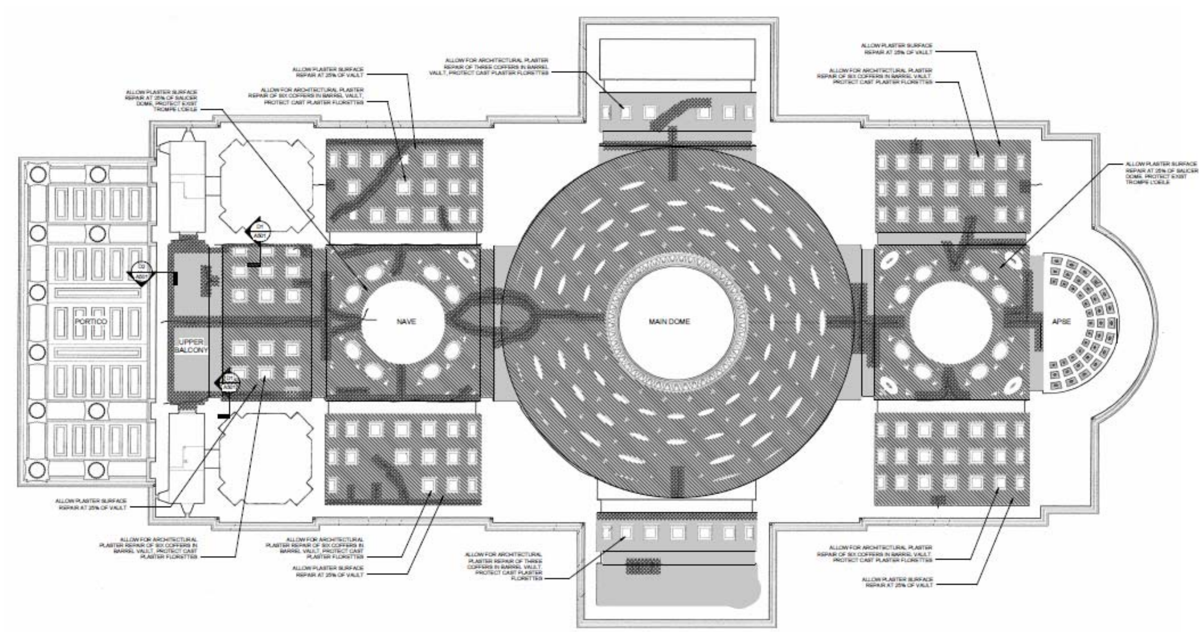

Figure 9. Reflected Ceiling Plan - Plaster / Masonry Crack Repairs.

Balancing a potentially invasive restoration and repair project with the importance of the Basilica to remain open to the public as a key landmark, popular tourist destination, and religious heart of the city, the design team faced a unique challenge.

Truss scaffolding was erected to provide work access to the domed ceiling and areas of cracked plaster while bridging the pews and worship spaces below.

Complete closure of the Basilica during the construction process was not an option: Sunday worship services were of fundamental importance to Baltimore's religious community, and canceling wedding that had been booked for months or years in advance was not possible. Instead, the Basilica was closed to the public during the work week, enabling construction activities to move ahead full speed. The construction team performed a weekly cleaning session every Friday before opening the Basilica to the public on weekends. A professional event coordinator was employed as part of the design team to convert the truss scaffolding into a visually acceptable display within the public worship space. Figs. 10 and 11 picture the erection of the scaffolding and final aesthetic modifications for worship.

Figure 10. Truss scaffolding erection over pews and main worship space.

Figure 11. Finished truss draping and protection during construction.

Fridays entailed a concentrated effort from the construction team, the event coordinator, and church officials to prepare the Basilica for public access. This included general construction site clean-up, such as dust removal, and securing all scaffolding access points from public entry, to entertainment audio set-up and arrangement of religious items.

Compared with similar construction activities with a five-day work week and option to push a schedule ahead on weekends, the construction team and, most importantly, the construction schedule were limited to a tight five-day work week with one day essentially dedicated for clean-up to reestablish public access and functional use.

Structural Repairs

Structural repairs included masonry crack injection, cementitious anchor rod pinning, repairs to cladding materials, and related finish work including plaster and painting.

Originally observed areas of cracked plaster noted on the construction drawings were further exposed during the construction process by plaster removal and exposing the brick backup structure. Cracks were chased out and appropriate repairs were applied based on crack location (masonry arch, masonry vault, masonry wall, etc.), extent and/or width of crack, and engineering direction though routine site visits.

In order to reestablish the load bearing capacity of the brick masonry elements, crack injection of brick and stone masonry was conducted were appropriate. Fig. 12 highlights a crack injection application within the Basilica.

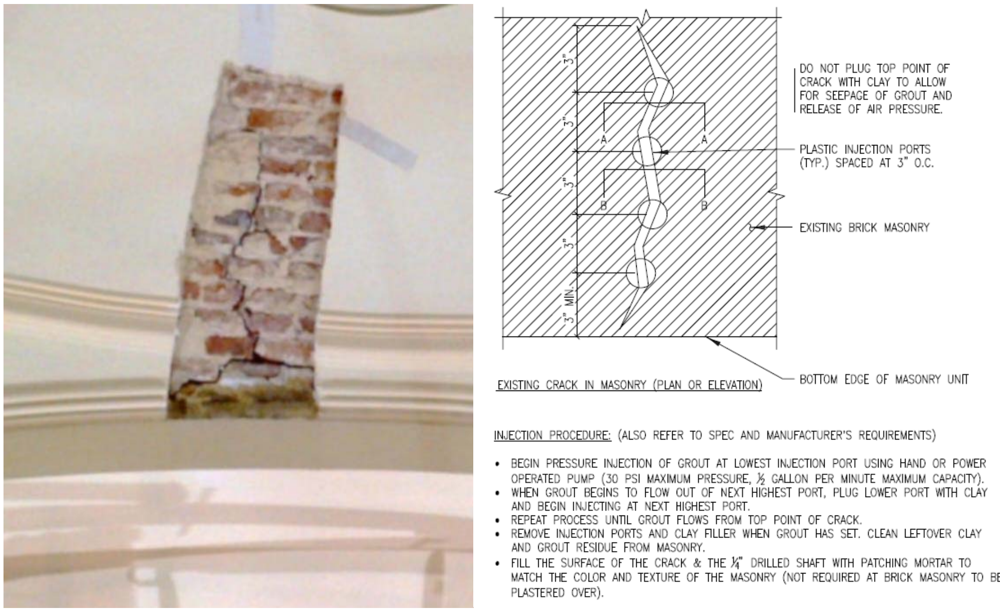

Figure 12. Masonry brick crack injection repair.

Key areas of distress were observed at the underside of brick arches. Fig. 13 shows typical cracking above brick masonry arches indicative of load reversal associated with seismic activities. Through additional investigation during the construction process, K&H observed this particular location to be a through-wall crack visible on the exterior of the building as indicated in Fig. 14. Due to the critical location at which the distress was observed, the keystone of the arch, repairs specified Cintec threaded anchors to cross-stich the compression arch and reestablish the intended load path (Fig. 14). However, before installing the Cintec anchors, the wall was scanned in-field to locate an existing tension ring. No tension ring was located at the area indicated for repair and thus the Cintec anchors were installed without jeopardizing the integrity of the masonry dome. The Cintec anchor repair is depicted in Fig. 15 with construction installation pictured in Fig. 16.

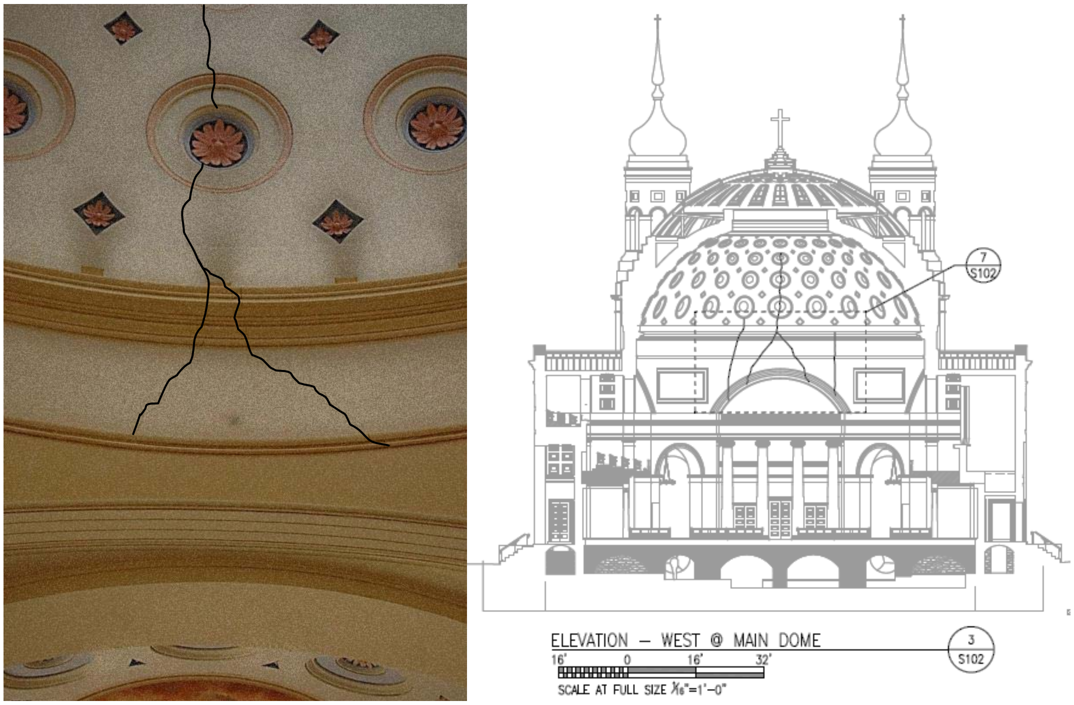

Figure 13. Typical cracking above brick masonry arch.

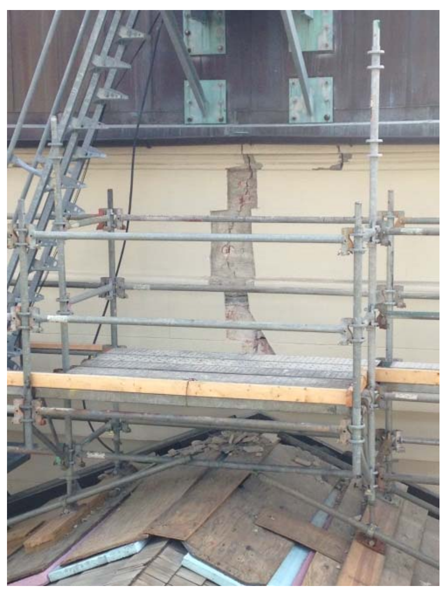

Figure 14. Exterior through-wall crack above brick masonry arch.

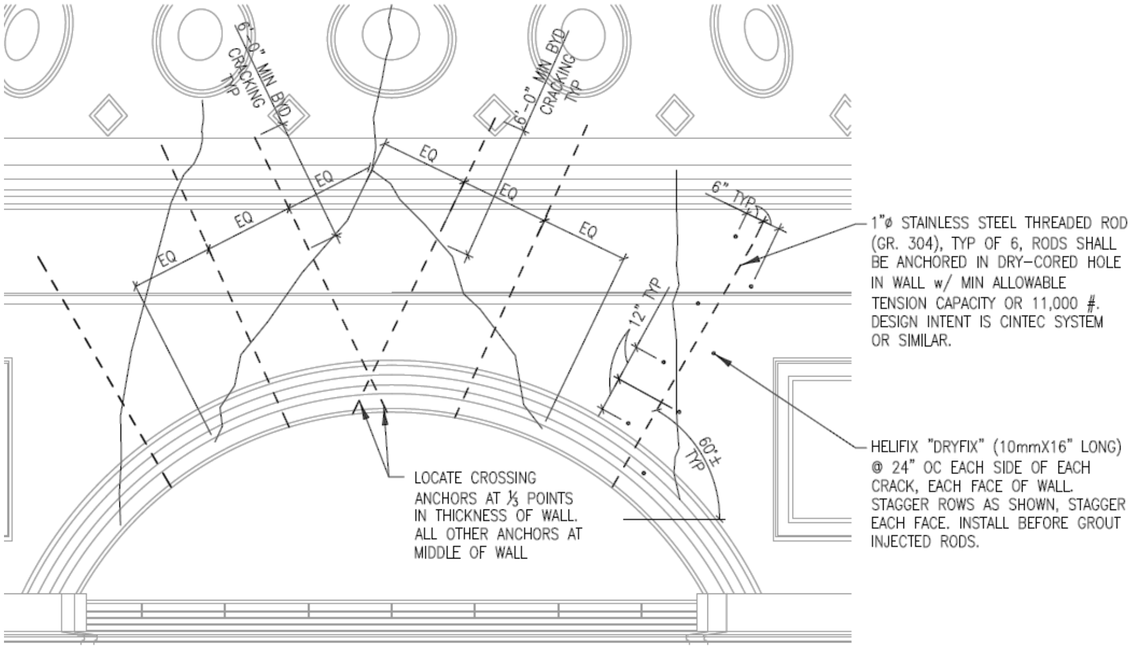

Figure 15. Cintec anchor arch stabilization.

Figure 16. Application of Cintec wall anchors for brick masonry arch repair.

Distress was observed at the transition of brick domes to barrel vaults, a critical load path transition area (Fig. 17). As a result of the weakened compression capacity at these areas, Helifix "DryFix" anchors were applied to bridge the crack separation of the brick domes to the brick vaults. Helifix "DryFix" anchors were also applied at areas of exterior wall separation from interior brick vault structure. The repairs as designed in the field are pictured in Figs. 18 and 19.

Figure 17. Masonry separation at brick dome connections to barrel vaults.

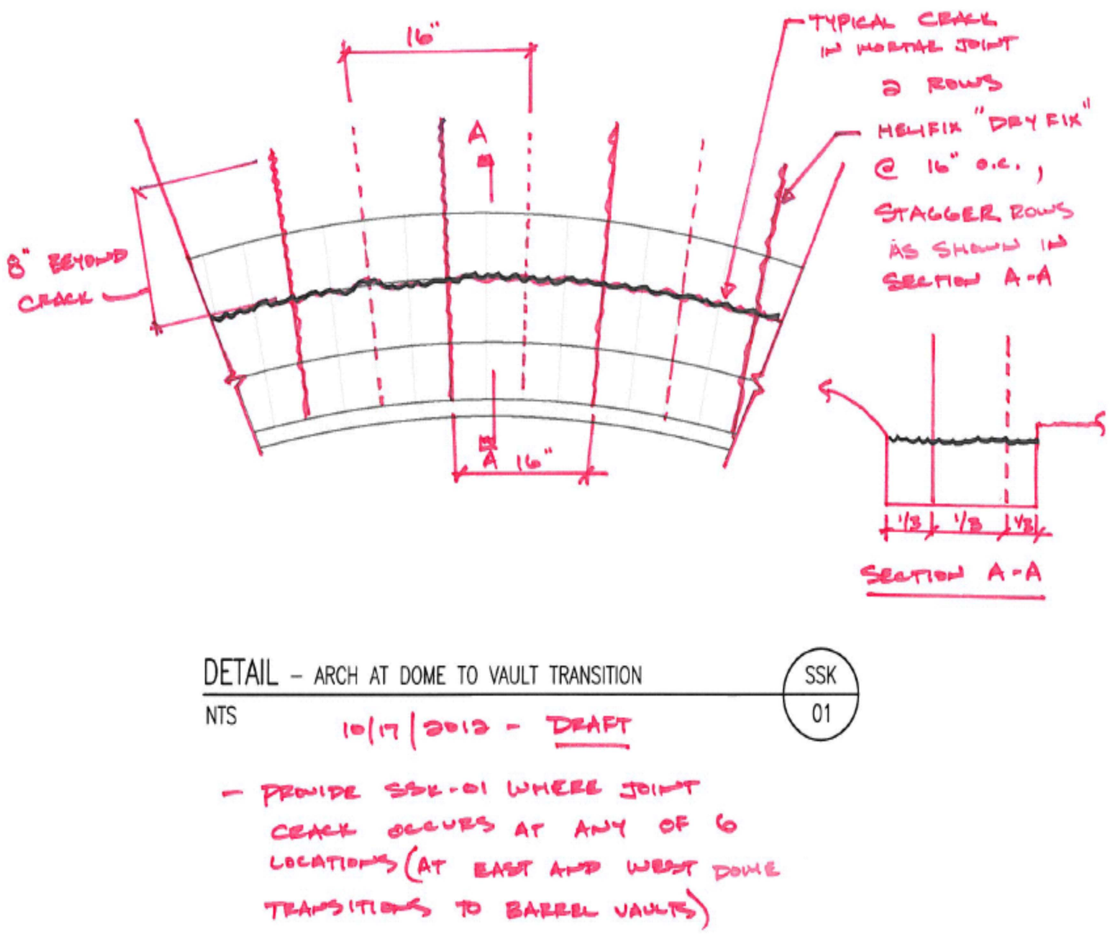

Figure 18. Arch to dome vault repair.

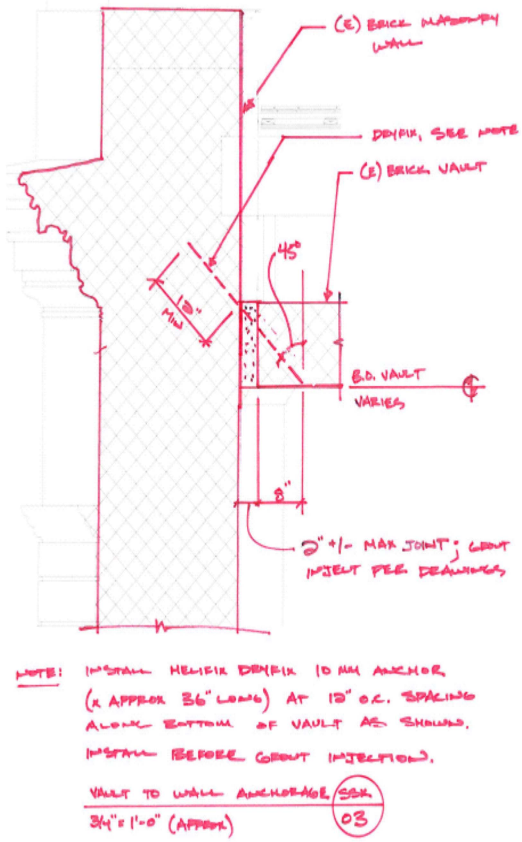

Figure 19. Barrel vault to exterior wall anchorage repair.

Vertical wall separation was observed at cold joints on either side of the main dome. Upon further investigation, a historical letter from Latrobe to Hayden, indicates the 8 main piers that support the dome had been incorrectly located during construction. As a result the dome was 8 inches longer in the north-south direction than the east-west direction. Latrobe promptly indicates this error as a botched legacy of the contractor [1]. The letter further states the construction error was fixed by reducing the dome size and by bringing "forward the piers both in front of the Niches & of the side Aisles" [1]. In other words, the vertical wall separation occurred at the cold joint of the main dome support piers. The cold joints themselves occur at the additional wythe of masonry added during construction to fix the contractor's error. This separation is pictured in Fig. 20.

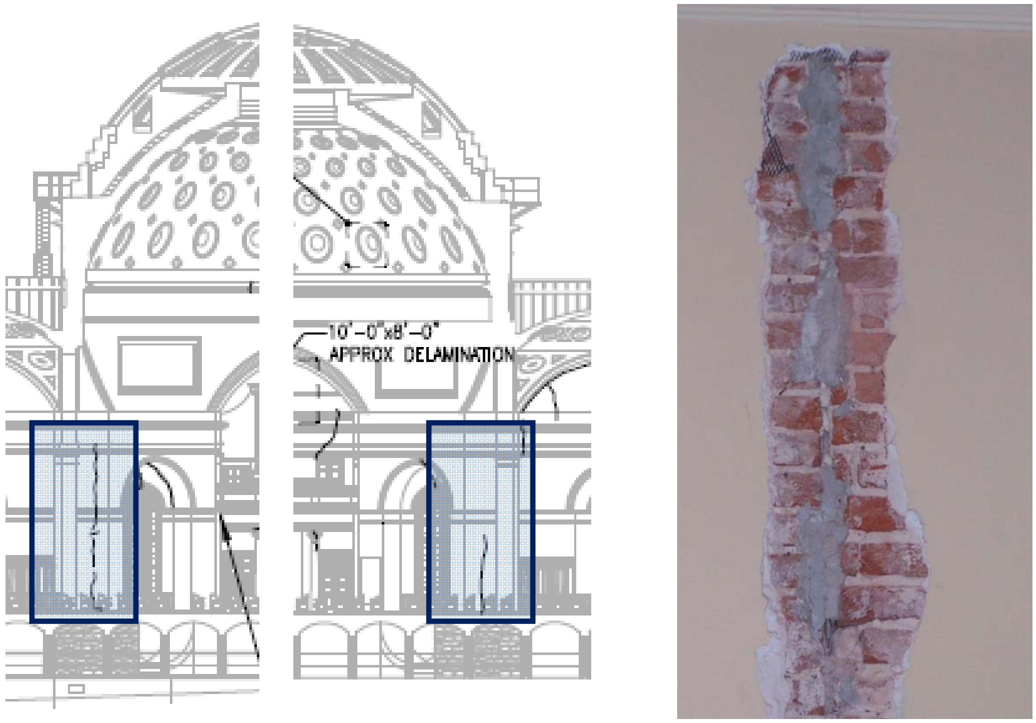

Figure 20. Vertical wall separation.

Stone cladding pinning, repair, and repointing was conducted around the exterior of the building at various locations including:

- Stone cornice cracking and separation,
- Marble door surroundings, and
- Exterior wall returns.

Repair to marble door surrounds is pictured in Fig. 21. Repairs were ground smooth after setting.

Figure 21. Marble door surrounds stone repair.

Exterior stone cornice separation is pictured in Fig. 22. Repointing was required at all areas exhibiting similar distress.

Figure 22. Exterior stone cornice separation.

Non-Structural Repairs

Non-structural repairs were conducted throughout the Basilica interior. As a result of structural repairs to the brick backup structure, numerous areas of ornamental plaster were removed. Having recently completed restoration of the plaster work and ornamental details within the Basilica, Hayles and Howe Ornamental Plasterwork and Scagliola was reemployed by the team to help repair earthquake-damaged or removed plaster elements associated with the repair process. Key areas requiring plaster repairs are pictured in Figs. 23-25.

Figure 23. Cornice plaster repair at brick masonry arches.

Figure 24. Cracking and plaster repair at main dome coffers.

Figure 25. Exterior bell tower dome cementitious repairs distress.

Following plaster repairs, the Basilica was painted corner to corner (full circumference of domes) in order to completely eliminate the visibility of repairs.

Conclusions

The repair and restoration of the Baltimore Basilica following the 2011 central Virginia earthquake is an example of historically and aesthetically sensitive repairs to a National Historic Landmark building complicated by its continued public use during the design investigation and construction activities. The project was substantially complete in time for an Easter 2013 grand re-opening and was completed within the original project budget, despite the limitations placed on the investigation phase.

Acknowledgments

Keast & Hood Co. would like to acknowledge the collaborative team effort of this project including:

- The Archdiocese of Baltimore,
- Cho Benn Holback + Associates, Inc.,
- James Posey Associates, Inc.,
- Hughes Associates, Inc.,
- Lewis Contractors,
- Hayles and Howe Ornamental Plasterwork and Scagliola,
- Cintec, and
- All subcontractor trades.

This work would not have been possible without such a fantastic team effort.

References

1. *The Baltimore Cathedral Historic Structure Report*. John G. Waite Associates, Architects PLLC, Albany, New York, 2000.