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Editor's Note

The members of Wiss, Janney, Elstner Associates' Difficult Access Team who rappelled down the Washington Monument are, *from left,* Erik C. Sohn, P.E., M.ASCE, Kathryn M. "Katie" Francis, David E. Megerle, Emma Cardini, P.E., M.ASCE, and Daniel A. "Dan" Gach, AIA.

THE DIFFICULT ACCESS Team (DAT) of Wiss, Janney, Elstner Associates, Inc. (WJE), is often called upon to use rappelling, climbing, and synthetic ropes to approach difficult-to-reach locations in order to assess exterior maintenance or repair needs. Training, of course, is of the utmost importance, and since its establishment in 1989 the DAT has used an internal three-level ranking system to characterize the expertise of its team members. For example, level I personnel move up to level II only after completing 100 hours of industrial rope access training and jobsite inspections. Personnel must also be capable of inspecting equipment and have a familiarity with general rigging and self-rescue techniques. Level III employees have regular and long-term involvement on DAT projects and are aware of all aspects of difficult access procedures and equipment.

In 2007 DAT members adopted equipment and procedures in conformance with guidelines set forth by the Society of Professional Rope Access Technicians, which dedicates itself to implementing certification programs, regulatory support, networking, and opportunities to participate in developing industry-consensus standards. The DAT includes a number of members who have obtained certification from this society, among them Emma Cardini, P.E., M.ASCE, a senior associate in the Boston office; Kathryn M. "Katie" Francis, an associate III in the Northbrook, Illinois, office; Daniel A. "Dan" Gach, AIA, a senior associate in the Denver office; David E. Megerle, a senior associate in the Denver office and the coordinator of the DAT; and Erik C. Sohn, P.E., M.ASCE, a senior associate in the Washington office—the five individuals who rappelled down the Washington Monument in late September and early October 2011 to assess its structural damage following the earthquake of August 23, 2011, centered near Mineral, Virginia.

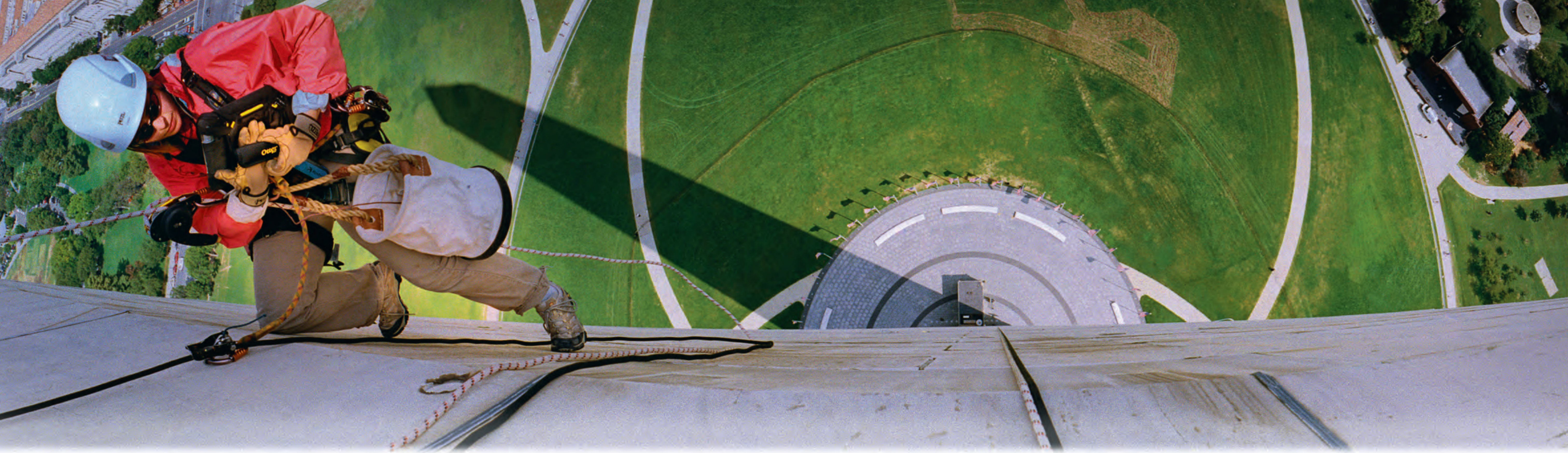
Since its completion in 1884 no one had ever before rappelled down the Washington Monument, and while the DAT members approached their tasks seriously, they also acknowledge being awestruck by the beauty of the nation's capital unfolding around them and by the privilege of working on what has long been considered the landmark that anchors the National Mall.

The work the WJE team performed on behalf of the National Park Service, the Washington Monument's official caretaker, is extremely significant—and extremely interesting, as evidenced by the article "Monumental Challenge," by Daniel J. Lemieux, AIA, R.A., M.ASCE, and Terrence F. Paret, M.ASCE, which begins on the following page. Once the interior assessment was complete, Megerle literally lassoed the monument to place the rope slings that would enable the team to rappel. Cardini, Francis, Gach, and Sohn were each assigned one of the monument's four faces to meticulously inspect the exterior block by block. Their work unfolded safely—a testament to their skill and training. (The only heart-pounding moment for the spectators assembled below occurred on the afternoon of September 30, when a strong gust of wind carried Sohn 30 ft from the west face onto the south face.)

The Washington Monument is not only a national landmark; it is a national treasure. Without doubt the work performed by this team of architects and engineers will help it endure as such for many years to come.

Anne Elizabeth Powell

ANNE ELIZABETH POWELL
Editor in Chief



FIRST PERSON

Monumental Challenge

On Tuesday, August 23, 2011, at approximately 1:51 PM (eastern daylight time), an earthquake with a moment magnitude of 5.8 was recorded by the U.S. Geological Survey within the Central Virginia Seismic Zone. Centered near Mineral, Virginia, approximately 84 mi southwest of Washington, D.C., the earthquake occurred at an approximate depth of 3.7 mi below the surface and was followed by several aftershocks with moment magnitudes ranging from 2.0 to 4.5. The U.S. Geological Survey has confirmed that this event was the most widely felt earthquake in U.S. history, and among the structures that sustained damage was the Washington Monument, long considered the centerpiece of the National Mall. This is the story of its postearthquake assessment, stabilization, and repair design.

By Daniel J. Lemieux, AIA, R.A., M.ASCE, and Terrence F. Paret, M.ASCE

AUGUST 23, 2011, began as a rather typical day, but early in the afternoon an earthquake struck—an event most at first took for the rumbling of a passing truck or subway train. Almost a year and a half after that earthquake occurred, those of us who live and work in Washington, D.C., and the surrounding region have similar recollections of that day, I suspect, and are reminded of both the unexpected and, in many respects, utterly surreal nature of that event. More important, however, is how fortunate all of us are that the event itself—despite its place in history—can fairly be characterized as insignificant relative to the widespread injury and loss of life that too often accompany the seismic events that occur more frequently on our West Coast and elsewhere around the world. In a city in which the immediacy of the September 11, 2001, terrorist attack on the Pentagon, the anthrax scare that ensued shortly thereafter, and the murders perpetrated in October 2002 by the Beltway snipers still lingers for many of us, the earthquake has occupied a far less personal and perhaps more abstract place in our collective subconscious. And yet for those of us who are architects and engineers, it was a sobering reminder of the significance of the landmarks that we have been entrusted to preserve and protect.

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While we had the good fortune to be entrusted by the National Park Service (NPS) with the initial assessment and development of stabilization and repair strategies for the Washington Monument, the Lincoln and Jefferson memorials, and other buildings and monuments in the NPS inventory, architects and engineers throughout our region faced similar challenges. Our story is a tribute to everyone who worked tirelessly to preserve landmarks throughout the Washington, D.C., area and surrounding regions. We consider ourselves fortunate to be a part of that community.

In contrast to interplate earthquakes, which are relatively common on the West Coast of the United States and occur along relatively well-understood plate boundaries within the earth's crust, the August 2011 seismic event that impacted Washington, D.C., and the surrounding region was an intraplate earthquake that occurred at some distance from a known plate boundary. Given the geology of the eastern seaboard of the United States, even moderate earthquake events will usually be felt across a far wider region than an earthquake of equivalent magnitude in the western part of the country, shaking an inventory of buildings that tends to be significantly older and more seismically vulnerable than the building stock in the West.

There are a number of scales commonly used to describe the size, magnitude, and intensity of an earthquake. Magnitude is a measure of the energy release associated with an earthquake at its source, and it can be measured in a variety of ways. The more commonly recognized Richter magnitude is

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David E. Megerle, *right*, the coordinator of Wiss, Janney, Elstner Associates' Difficult Access Team, begins the process of placing a series of nylon slings around the top of the pyramidion. Emma Cardini, P.E., M.ASCE, assesses the east face of the monument.

measured using a logarithm of the amplitude of waves recorded by seismographs, while moment magnitude is based on the area of "slip" along a fault. As a measure of the energy release associated with an earthquake at its source, however, magnitude measures provide more meaningful information about the general strength of the earthquake as a geological event than about the strength and character of ground shaking at any particular location. The Modified Mercalli Intensity (MMI) scale is a largely qualitative assessment of the effects of the earthquake in any given locale. While a given earthquake typically has only a single magnitude value associated with it, an MMI level can be assigned to each and every location in a shaken region. The MMI scale narratively describes both the range of human perceptions associated with locally felt ground shaking and the effects of the ground shaking on the built environment. For example, the August 23 earthquake, which was assigned a moment magnitude of 5.8, caused a shaking intensity at the epicenter that had a value of VII on the MMI scale and a value of V for much of Washington, D.C. An MMI value of VII is defined on the MMI scale as "damage negligible in buildings of good design and construction; slight-to-moderate in well-built ordinary structures [and]; considerable damage in poorly built or badly designed structures, [with] some chimneys broken."

In addition to the MMI scale, the intensity of local ground shaking can be measured by instruments, thus allowing the ground motions to be quantified. While there is undoubtedly a relationship between the nature of the ground motion caused by an earthquake and the damage sustained by affected buildings, it is different for each building because it depends in part on the properties of the building itself. In general terms the maximum acceleration of the ground, or "peak ground acceleration," is commonly used by earthquake engineers to characterize the local intensity of shaking during an earthquake and can be loosely correlated to the MMI scale using the "instrumental intensity" map available from the U.S. Geological Survey and referred to on its website as a ShakeMap.

The August 23 earthquake's ShakeMap (http://earthquake.usgs.gov/earthquakes/shakemap/global/shake/082311a/) provides a valuable tool for estimating peak ground acceleration values in the Washington, D.C., area during that seismic event, especially since relatively few recording instruments were operational during the event. Seismologists have developed methodologies to quantify the shaking intensity at any particular locale by extrapolating from data recorded at other locations, and this technology is used to construct the U.S. Geological Survey ShakeMaps. The map indicates that the range of estimated peak ground accelerations within Washington, D.C., would correlate roughly to a "moderate" level of perceived shaking and "very light" potential for damage. Structural damage resulting from shaking having an MMI value of V is rare and usually does not occur in competently engineered structures. However, certain unique structural characteristics of the Washington Monument rendered it unusually vulnerable to earthquake-induced ground motions.

Our final seismic assessment supports the conclusion that there is negligible risk of the monument experiencing a global loss of stability or large-scale collapse. The soils that support the monument do not appear to be at all at risk, and only minor tensile stresses that would, at worst, result in bed joint cracking in the midheight section of the monument shaft are predicted below the 450 ft level, where header courses extend the full width of the shaft walls, creating a condition that is quite dimensionally stable and, therefore, not inherently prone to disintegration. Above the 450 ft elevation, potential earthquake damage and risk become somewhat more nuanced; however, our final assessment concludes that there is little risk of damage above the 450 ft elevation placing visitors in jeopardy.

Cracking is visible on a marble panel unit at course G on the west elevation of the pyramidion (stone W. 529.2).

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Daniel A. "Dan" Gach, AIA, descends the south face of the monument during his assessment.

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Our story is a tribute to everyone who worked tirelessly to preserve landmarks throughout the Washington, D.C., area and surrounding regions.

BEGUN ON JULY 4, 1848, and halted for a period that coincided, in part, with the Civil War, construction of the Washington Monument was completed in 1884. At 555 ft 5 $^1/_8$ in. tall, the obelisk remains the world's tallest unreinforced stone masonry structure. Originally conceived by the architect Robert Mills as a tribute to Washington's military leadership that would include, according to NPS documents, a "nearly flat-topped obelisk surrounded by a circular colonnade on which would stand a statue of Washington in a Chariot" and statues of 30 prominent Revolutionary War heroes displayed inside the colonnade, the monument as it exists today is both a reflection of the vision carried out by Mills's successor, Lieutenant Colonel Thomas L. Casey, and a by-product of the political turmoil and lack of funding that plagued the project from 1856 to 1876. Redesigned to include only the classical proportions of an unadorned Egyptian obelisk, construction of the monument resumed in April 1880, a milestone memorialized to this day by the slight color change visible in the exterior marble at about the 150 ft level, where four rows of marble supplied by the Lee marble quarry, in Sheffield, Massachusetts, had originally been installed before cost, among several other factors, dictated a return to the quarries from the geological formation near Cockeysville, Maryland, that had supplied the original exterior stone. Although historical accounts of that time period vary, a report prepared by the NPS in 2004 entitled *Washington Monument and Associated Structures, Historic Structure Report, Vol. 1, Washington Monument,* tells us:

> Prior to laying new masonry, approximately 6 feet of existing masonry, or 3 courses, were removed from the top of the shaft down to a height of 150 feet. The mortar in these courses had begun to deteriorate from the action of frost and weather. The

stones at these courses were small and were believed to be refuse material from the first period of construction. The inner core of rubble gneiss and mortar from the 1854 construction was then removed from the top course of existing masonry, and the core was filled with a [p]ortland cement grout to fill any cavities and to form a level base for the new construction. The shaft wall was then reset beginning at the 150-foot level to the diminished thickness required in the new design plans. . . .

Between the 150-foot and 170-foot levels, the center shaft was widened approximately 6 feet by reducing the thickness of the walls. The wall thickness tapered from 8 feet 7-$^1/_2$ inches at the 160-foot level to 1 foot 6-$^1/_2$ inches thick at the 500-foot [observation deck] level. The walls of the obelisk between the 150-foot and the 452-foot level were bonded, ashlar masonry in 2-foot-high courses consisting of an outer wythe of white marble and inner wythes of granite. Above the 260-foot level, the marble headers extended through the entire wall to the face of the interior shaft. From the 440-foot to the 452-foot levels, galvanized iron cramps were "freely used" to reinforce adjacent stones of the masonry wall construction. Above the 452-foot level, the thinning monument walls were constructed of a single wythe of marble. The upper 30 feet of the shaft masonry was strengthened with mortises and tenons in order to support the ribs of the [p]yramidion. The marble laid at the 150- through 170-foot levels was originally finished by rubbing to match the earlier work. Above the 170-foot course, stones were tooled with a chisel, and the stones at the 150–170-foot courses were later retooled with a chisel to match.

With the United States Capitol in the background, members of Wiss, Janney, Elstner Associates' Difficult Access Team descend the Washington Monument.

Completion of the monument was celebrated on December 6, 1884, with the placement of a capstone of cast aluminum—considered at the time a precious metal more valuable than platinum—and the capstone served as part of the original means of lightning protection for the structure. The capstone, which was placed at the top of the pyramidion, the pyramid-shaped uppermost portion of the monument, is engraved on each of its four faces to record its construction. The west face reads: "Corner Stone laid on bed of foundation, July 4, 1848. First stone at height of 152 feet laid August 7, 1880. Capstone set December 6, 1884." The east face reads: "Laus Deo" (Praise be to God). The north and south faces are engraved with the names of the commission and the key men involved in the monument's construction. The monument was formally dedicated on February 21, 1885, and opened to the public on October 9, 1888. It was added to the National Register of Historic Places on October 15, 1966, and has undergone a series of cleaning and preservation programs that began in the early 1930s with the erection of an external steel framework to allow abrasive cleaning of the exterior stone and culminated with an extensive preservation effort between 1998 and 2001 that is widely remembered for its use of an external scaffolding system designed with the creative input of the architect Michael Graves to symbolically reflect the overall proportion and joint pattern of the underlying stone obelisk. Engineering support was provided by James Madison Cutts Consulting Engineers, in Washington, D.C., and the scaffolding team of Universal Builders Supply, Inc., in Cheverly, Maryland. (See "Scaling the Monument," by Mark J. Tamaro, P.E., and John G. O'Connor, *Civil Engineering,* April 1999, pages 36–41.)

The two largest pieces of stone to be safely removed from the monument were located adjacent to one another at the 490 ft level. They were at the southeast corner on the east elevation.

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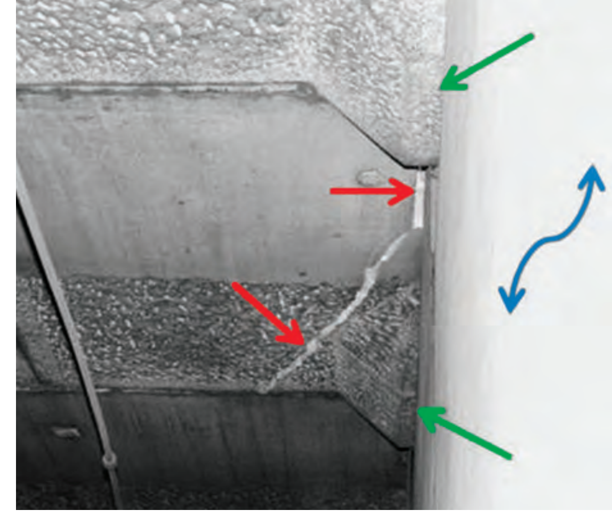
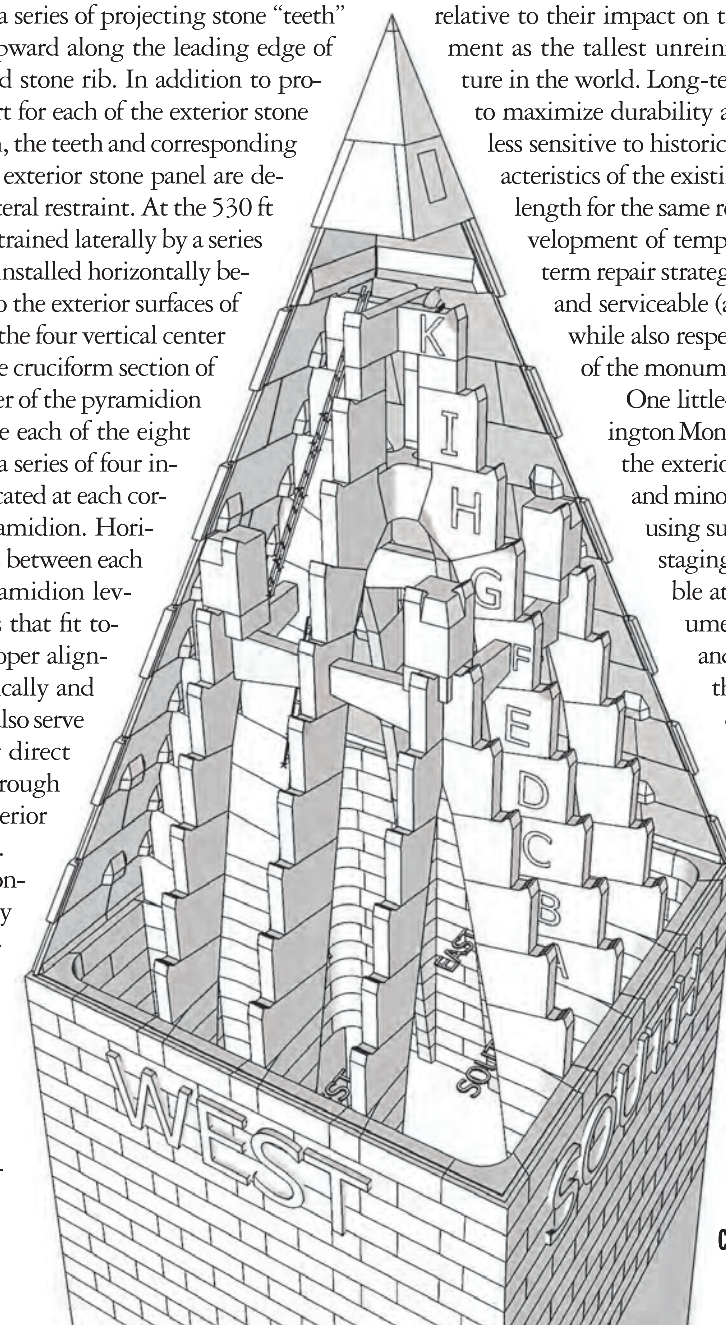
The pyramidion is supported by a series of corbeled stone "ribs" that begin at the 470 ft level and extend upward to a point just below the apex of the monument at approximately the 550 ft level. A total of three ribs exist at each elevation and, between the 470 and 500 ft levels, extend into and are fully integrated with the exterior stone panels at those elevations. Above the 500 ft level at the sloping exterior surfaces of the pyramidion, each exterior stone panel includes a single, integral stone "lug" centered on the inboard surface at the base of each panel. This lug rests on a series of projecting stone "teeth" that extend vertically upward along the leading edge of each underlying corbeled stone rib. In addition to providing dead-load support for each of the exterior stone panels at the pyramidion, the teeth and corresponding inboard surfaces of each exterior stone panel are designed to also provide lateral restraint. At the 530 ft level each stone rib is restrained laterally by a series of large stone tie beams installed horizontally between each rib parallel to the exterior surfaces of the monument. Each of the four vertical center ribs converges on a single cruciform section of stone located at the center of the pyramidion at the 540 ft level, while each of the eight corner ribs converges at a series of four individual cornerstones located at each corner, or "hip," of the pyramidion. Horizontal and vertical joints between each of the panels at the pyramidion level include rebated edges that fit together so as to allow proper alignment of the panels vertically and at each corner, and they also serve to mitigate the risk for direct rainwater penetration through those joints into the interior spaces of the monument.

The Washington Monument's place in history as one of the most recognizable and frequently visited landmarks in the United States figured prominently both during our initial condition assessment and temporary weatherization effort and during the development of the drawings and technical specifications that will guide its long-term repair and preservation. Rope-access techniques and temporary weather protection measures developed and implemented in the days and weeks immediately following the earthquake were expressly designed to protect the health, safety, and welfare of our team while minimizing the impact of weather and the protection measures themselves on the historic fabric of the monument. Temporary stabilization concepts that focused only on structural reinforcement in areas that would never be seen by the general public were debated at length relative to their impact on the significance of the monument as the tallest unreinforced stone masonry structure in the world. Long-term repair strategies intended to maximize durability and performance but perhaps less sensitive to historic fabric and the material characteristics of the existing stone also were debated at length for the same reasons. The result was the development of temporary stabilization and long-term repair strategies that are technically sound and serviceable (and reversible when possible) while also respecting both the historic fabric of the monument and its place in history.

One little-known fact about the Washington Monument is that it is accessible on the exterior for close-range observation and minor repair below the pyramidion using suspended scaffolding, or swing staging. Core holes through the marble at the 490 ft level of the monument are testament to this fact, and though currently filled with the original stone core extracted from each location during a previous preservation effort, they remain accessible from the interior and available for reuse. In fact, while many who observed the preservation effort completed in 2000 came to appreciate the pipe scaffolding designed with the creative input of architect Michael Graves and the engineering support provided by James Madison Cutts Consulting Engineers and



Red arrows indicate a crack at course G on the west elevation of the pyramidion (stone W. 529.2); green arrows indicate the knuckles; the blue arrow indicates the rib. The illustration below indicates the interior construction of the pyramidion as viewed from the west face.



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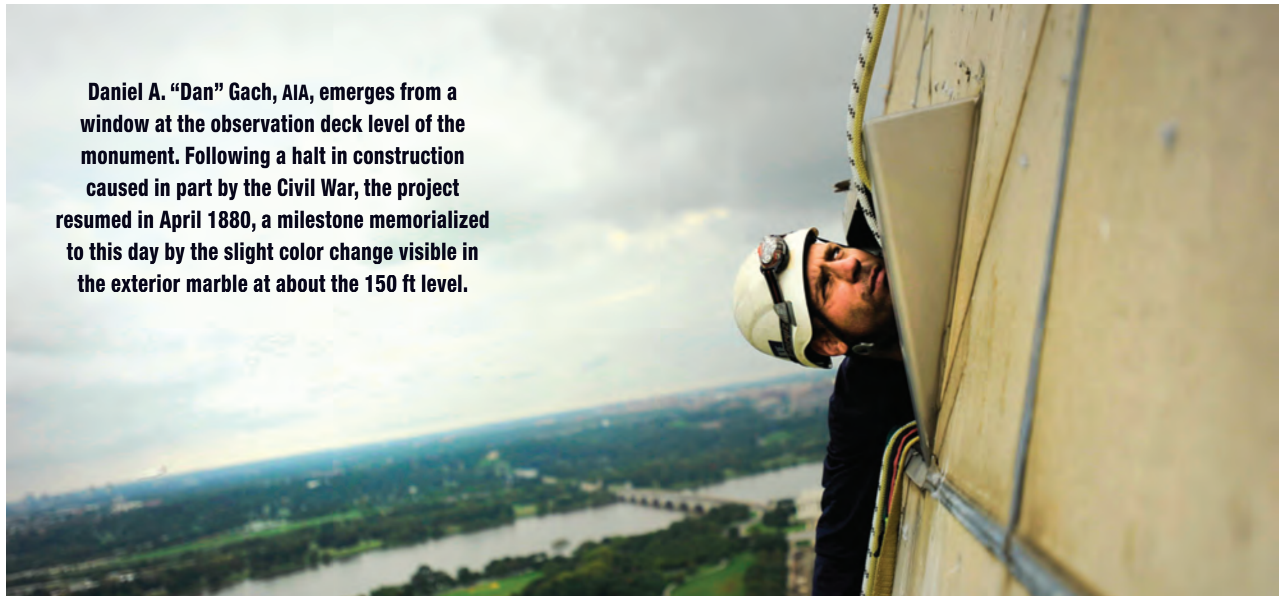

Daniel A. "Dan" Gach, AIA, emerges from a window at the observation deck level of the monument. Following a halt in construction caused in part by the Civil War, the project resumed in April 1880, a milestone memorialized to this day by the slight color change visible in the exterior marble at about the 150 ft level.

the scaffolding team at Universal Builders Supply, most were unaware that the scaffolding itself served as an exoskeleton for swing staging that provided direct access to the vast majority of the exterior surfaces of the monument during that intervention.

In the hours and days immediately following the earthquake, all options for access to both the interior and the exterior surfaces of the monument were on the table. However, after carefully weighing the potential significance of the damage already in plain view at the top of the monument and the immediacy of our concerns relative to the structural integrity of those conditions and the likely fall hazards, the decision was made to use rope access for the initial condition assessment of both the interior of the pyramidion and the exterior of the monument. Barely 24 hours after we received the first call from the NPS following the earthquake, a team of engineers and architects from Tipping Mar, of Berkeley, California, and the San Francisco, Denver, and Washington, D.C., offices of Wiss, Janney, Elstner Associates, Inc. (WJE), entered the monument to begin the initial survey. As part of that effort—and with the threat of Hurricane Irene just days away—our team also completed the temporary installation of joint sealant along cracks and open joints visible on the inboard side of the exterior stone cladding where movement had resulted in damage to the stone or where the loss of joint mortar created a direct path for rainwater into the interior.

PERHAPS STATING THE obvious if only to underscore the significance of the assignment, Kent K. Sasaki, P.E., S.E., M.ASCE, the principal and unit manager of WJE in San Francisco, responded as follows: "Get our best, most experienced people on this job." Sasaki received the first call following the earthquake and has worked closely with the NPS on seismic assessment projects from his office in San Francisco. He then called on David E. Megerle, a senior associate in WJE's Denver office and the coordinator of the firm's Difficult Access Team (DAT), to begin the process of assembling a team and planning our rope-access efforts. Megerle, who himself was busy at the time leading a small team of rope-access professionals on a condition assessment of a state capitol dome, immediately began updating the rope-access and safety plan he had developed several years ago (prior to September 11, 2011) as an option for close-range assessment and instrumentation of the monument. Working closely with Lee Farrell, an associate principal and director of safety for WJE, and several members of the NPS project team, Megerle developed a rope-access and safety plan that addressed both the challenges unique to the monument and its location on the National Mall, as well as the many personnel- and security-related risks that, since September 11, 2011, remain of particular concern not only to the NPS but also to the U.S. Park Police (USPP) and U.S. Secret Service. A team of architects and engineers with specific experience in condition assessment of

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Emma Cardini's Account

INSPECTING THE WASHINGTON MONUMENT from ropes was a highlight of my career. I will never forget the awe I felt when I began my first ascent to the top of the pyramidion. The sheer mass of the structure is enough to inspire even the youngest of engineers, but the history behind it is almost as fascinating.

I had the luxury, as some would say, of inspecting the east facade of the monument. Prior to arriving on-site, we had each selected a side to survey. Being fair-skinned and concerned about long periods of sun exposure, I had requested the face that had the least amount of sun. Since someone else had chosen the north facade prior to my request, I was given the east. The reason others would have called this a luxury is due to the fact that the windows on the east face of the pyramidion are 6 in. taller than those on the other faces. This made a big difference when trying to climb out of them with all of our equipment to begin our ascent or descent. In addition, the majority of the media vans were stationed on the east side of the Monument, so I had many of the cameras pointed at me for hours of a time. I would not say that this was exactly a luxury, but as a result I have several great photographs that document my experience.

The planning of Washington, D.C., was never as clear to me as it was from 500 ft up on the monument. I could literally see Pierre L'Enfant's plan around me. Being an avid driver in Boston, I appreciate any plan that has parallel streets and a recognizable pattern, and the L'Enfant plan also highlights the beautiful memorials, fountains, and monuments throughout the nation's capital.

Though I have respect for working at height, I have never experienced a natural response while doing so, and thus the height of the monument did not feel any different than inspecting a building 100 or 300 ft tall. The only sense of anxiety I felt was from the media. Not only did several news stations have live streams following our every move, but some of the reporters had very little respect for personal space. This was not always the case, and we met several who casually dropped by to ask questions. However, their presence caused us to change how we planned our days.

I have a deep respect for the original builders and designers and am thankful that the most widely felt earthquake in U.S. history did not cause more damage.

Life did not pause for our inspection. I was still in the process of selling my condo after just having moved into our new house with my husband. In fact, I flew to D.C. the day after we moved in, leaving him alone to unpack for the next two weeks. Being a structural engineer himself with experience that includes inspecting at height, he was also a great resource for an Associated Press article about his feelings of the work done by Wiss, Janney, Elstner Associates, Inc., on the monument. It is a great feeling to have his support and understanding of my work.

The biggest strategic difference in accessing the monument from other difficult access inspections we have performed is the lack of projections on the surface of the structure. Typically, we inspect structures that have a series of windows or projecting elements to temporarily redirect our ropes or relieve some of the weight in our legs. Below 500 ft there was nothing except the first-floor entrance roof. This meant we had to be very intentional as to where our rappelling drops were planned. We had some flexibility to move side to side, but if we had to inspect anything beyond reach and close-up, the best option often involved redirecting ourselves using the weight of our colleagues.

I am grateful for this opportunity and will always have a fond affection for both the Washington Monument and the Washington National Cathedral, which we also inspected. I also have a deep respect for the original builders and designers of these structures and am thankful that the most widely felt earthquake in U.S. history did not cause more damage. Though the monument was not designed for earthquake loads, the knowledge of the designers and the care of the craftsmen were the reason that the visitors in the observation deck were relatively safe during the earthquake.

Emma Cardini, P.E., M.ASCE, is a senior associate in the Boston office of Wiss, Janney, Elstner Associates, Inc., and a member of the firm's Difficult Access Team.

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historically significant buildings and structures and certified by the Society of Professional Rope Access Technicians as level II and level III rope-access lead technicians and supervisors was assembled for the project. The team members had more than 5,000 hours of combined experience in rope-access work. After arriving on-site, Megerle served as the rope-access supervisor for our team; Farrell was in charge of safety and coordination with the NPS and the USPP. The lead technicians responsible for our exterior rope access were Emma Cardini, P.E., M.ASCE, a senior associate in our Boston office; Kathryn M. "Katie" Francis, an associate III in WJE's Northbrook, Illinois, office; Daniel A. "Dan" Gach, AIA, a senior associate in our Denver office; and Erik C. Sohn, P.E., M.ASCE, a senior associate in our Washington, D.C., office.

The equipment necessary to complete our work was assembled and immediately shipped to Washington, D.C., from various project locations around the country. It was then subjected to security screening by the USPP at the fence line established as a security perimeter around the base of the monument following the earthquake before being transported to the 500 ft level observation deck inside the pyramidion for rigging. During that time, an advance team from WJE in Washington, D.C., and the NPS worked together inside the pyramidion to temporarily remove and reinstall both the observation deck windows and the removable stone panel at the south slope of the pyramidion (the south hatch) to ensure access to the exterior of the monument for our DAT prior to its arrival. By working primarily through the south hatch of the monument, temporary protection boards were installed at each of the four hips of the pyramidion to protect the existing lightning protection system, followed by the placement of a series of nylon "slings" around the top of the monument that were secured with a secondary line through the south hatch to the interior structure. A total of six slings were installed around the top of the monument, two slings assigned to each DAT member at the north, east, and west facades to serve as independent points of suspension for respectively their main and secondary lines. The main support and fall protection lines at the south facade were secured directly through the south hatch to the underlying structure. An optional third available suspension point for each DAT member was also created using a line extended around the circulation core (elevator shaft) at the observation deck level inside the monument.

Daniel J. Lemieux, AIA, R.A., M.ASCE, the architect and project manager for the post-earthquake assessment, stabilization, and repair design of the Washington Monument, holds a large piece of stone with visible characteristics that are consistent with stone extracted from the Cockeysville, Maryland, region.

Following a safety briefing each morning with members of our DAT and representatives of the NPS and the USPP, anchors and rigging were checked and resecured as necessary both within and outside of the pyramidion, after which the DAT members "geared up" at the observation deck level, checked one another's harnesses and related personal safety equipment, and then separated and attached themselves to the main and secondary lines that were hung past an observation deck window at each facade of the monument. Team members were then assisted through each of those windows to begin their condition assessment work on the exterior of the monument. This unique approach, which Megerle described as something akin to rigging a candlestick, was thoroughly reviewed in advance by rope-access specialists on staff with the NPS, as well as by representatives of the Washington, D.C., fire and emergency medical services, prior to beginning our work.

The survey itself began on September 26, 2011, and included not only a close-range visual assessment and documentation of the exterior stone surfaces of the monument but also the removal of small sections of stone and joint mortar loosened by the earthquake that were accessible for safe removal by hand during the survey. The

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Teamwork, focus, and an unrelenting attention to detail on the part of the various team members—particularly in the face of growing local and national media attention—were critical to the overall success of our initial rope-access condition assessment effort.

mapping of cracks and detailed documentation of loosened stone dutchman units—small sections of stone dressed and finished to fit neatly into larger sections of dimension stones where irregularly shaped spalls once existed—incipient spalls in the stone, and partially debonded joint mortar and stone mortar patching material were facilitated through the use of tablet personal computers and direct radio communication with a ground crew composed of Kelly Cronin and Erin Ward of WJE's Washington office and Melanie Pyle of WJE's Atlanta office. The three were positioned to record the observations of each DAT member and overlay those observations onto a copy of documentation from the most recent major preservation campaign of the monument, in 1999 and 2000. Our final rope-access drops were completed on October 5, 2011.

Teamwork, focus, and an unrelenting attention to detail on the part of the various team members—particularly in the face of growing local and national media attention—were critical to the overall success of our initial rope-access condition assessment effort. In fact, it was largely through the cooperation and support of the USPP's Captain Kathleen Harasek and the officers under her command that we were able to successfully complete this work. Operating primarily from a mobile command center delivered specifically to support our work, Harasek and her team provided us with real-time weather data via a direct link to the National Oceanic and Atmospheric Administration, daily escorts when necessary to and from the monument through the crowd of reporters and cameramen assigned to cover the project, and, perhaps most critical of all, daily communication and coordination with the White House and the U.S. Secret Service regarding our activities on the monument and helicopter traffic to and from the White House grounds.

David E. Megerle, the coordinator of Wiss, Janney, Elstner Associates' Difficult Access Team, adjusts the slings secured around the top of the pyramidion that served as anchors for the team.

One consequence of the decision to use rope access that we considered but clearly underestimated as the work began to unfold was the amount of local, national, and international media interest that would be generated. Prior to beginning the project, we recognized that any level of rope-access work on the exterior of the monument would be unprecedented

Members of Wiss, Janney, Elstner Associates' Difficult Access Team all remarked on the spectacular views they had of the nation's capital, as evident by the backdrop behind Daniel A. "Dan" Gach, AIA, as he works on the south face of the monument.

and, therefore, garner some level of local media interest. However, the day-to-day coverage of our team, the around-the-clock live video feed of our work, and, at times, the relentless pursuit of our team members for interviews and additional insight regarding the damage to the monument constituted a challenge that we never could have anticipated and one that required a continuous and coordinated effort on the part of WJE, the NPS, and the USPP.

During the planning stages of the project, we recognized that photo and video documentation of our findings, both for evidentiary purposes relative to the effect of the earthquake on the monument and to facilitate the development of our final report and recommendations for stabilization and repair, would be critical. We also recognized the historic significance of the moment for the NPS. While we had used rope access on many historically significant buildings and structures across the country and around the world, none would capture the interest and imagination of so many as the work on the Washington Monument. For those reasons, we chose to retain the services of Colin Winterbottom Photography, of Washington, D.C., for professional still photographs and Creative Liquid Productions LLC, of Alexandria, Virginia, for video that would document our rope-access work and be independent of the images that the members of our DAT would generate.

The NPS also recognized the historic significance of the moment and, more important, its own responsibility to keep the public fully informed regarding our work and the significance of the damage already visible on the exterior of the pyramidion, as well as any additional damage that we observed during the course of our work. Consequently, Carol Johnson, the media liaison for the NPS, reached out to us for assistance in coordinating and managing that effort. Her goal, like ours, was to make certain that the information conveyed to the public was technically accurate and that the images posted on the NPS website and offered to print, broadcast, and cable media were presented in the proper context. The process that unfolded was advantageous in that it allowed us to utilize our still photography and videography team both to document our own work and to evaluate—in real time and at the end of each workday—the conditions observed on the monument and their significance relative to the earthquake versus conditions that could reasonably be attributed to normal weathering of the stone, previously installed stone mortar patches, joint mortar, and sealant. The process also enabled the USPP to review the same material for security purposes to ensure that the images selected for release to the general public did not inadvertently reveal conditions inside the pyramidion considered sensitive by the USPP and the U.S. Secret Service.

IN THE WEEKS LEADING UP to our rope-access effort, we worked closely with the NPS to prepare a summary of our initial condition assessment. We then assisted with the preparation of a press release outlining our rope-access mission and, after completing a technical review of the remarks prepared by Robert "Bob" Vogel, the superintendent of the National Mall, we joined Vogel and other representatives of the NPS in a press conference to discuss the damage observed to date and our objectives for the project. During this process, we made it clear that direct access to our team by the media would be prohibited until our work was complete. This was considered necessary both from a "mission" perspective—that is, we had a job to do—and from a safety perspective. While rope access is, in many respects, one of the safest techniques for performing an exterior condition assessment, minimizing any distractions to those responsible for performing this type of work is important and was considered particularly critical on the monument given the technical challenges presented by its height and the unique manner in which it would have to be rigged.

We recognized that any level of rope-access work on the exterior of the monument would be unprecedented and, therefore, garner some level of local media interest.

After just 24 hours on-site it became clear both to the members of our team and to the NPS that media interest in our work would remain intense. Unless allowed an interview with one or more members of our team, media interest would escalate into a distraction that could influence the focus of our team and, perhaps, delay the completion of our work. As if to underscore the seriousness of that concern, reporters who had gathered for the press briefing held late on Monday, September 26, to listen to our summary of the day's events collectively ignored our request to give the members of our rope-access team space as they exited the monument and instead chased them down in attempts to interview them. Fortunately, the USPP intervened and provided our team with an "escort" of sorts to Survey Lodge Ranger Station (south and a bit farther west of the monument), where several additional reporters had gathered after learning that our vehicles were parked nearby.

Largely in response to this event, we met immediately with Johnson and, later, with Harasek to reassess the protocol we had established for our interaction with the media. We agreed to make one or more members of our rope-access team available for a series of very brief interviews with representatives of the assembled media. Johnson coordinated that effort on behalf of the NPS and selected a location near the Jefferson Memorial for the interviews, in part to remain out of plain view of the crowds that had begun to gather each morning at the monument to watch our work but also to avoid creating a significant distraction during the morning rush hour.

As we had hoped, granting media access to our DAT had an immediate and beneficial impact on the project: it diminished what had become a rapidly escalating distraction for our team and, more important, allowed us to head off a handful of false reports regarding the seriousness of the damage being observed on the monument. The ability to work closely with the NPS, the USPP, and our team of photographers to review and disseminate images and information on a daily basis summarizing our work in a way that was both compelling and technically accurate became an extremely valuable tool for us in the field. It afforded members of the media direct access to reliable information regarding our work, and it gave the NPS a vehicle for keeping the public fully and accurately informed regarding our progress.

Kathryn M. "Katie" Francis performs assessment work on the north face of the monument.

COLIN WINTERBOTTOM (WWW.COLINWINTERBOTTOM.COM) AND MATTHEW GIRARD (WWW.MATTHEW-GIRARD.COM) COURTESY OF WISS, JANNEY, ELSTNER ASSOCIATES, INC. (WWW.WJE.COM), BOTH

OUR INITIAL SURVEY of the Washington Monument and our review of the documentation made available to us by the NPS in the immediate aftermath of the earthquake indicated that the structure itself remained fundamentally sound with no visible evidence of substantial structural distress. After completing our close-range assessment and removing small sections of stone and loosened joint mortar through rope access, that opinion remained unchanged. However, the nature and extent of the damage at the pyramidion, particularly with regard to the number of cracks, spalls, and incipient spalls—in this instance, small fragments of stone varying in size, shape, and depth from the exposed surface of the stone that had become partially separated from the parent section of stone and could be identified visually and confirmed audibly through sounding—caused concern, as did the planar displacement of the exterior marble in areas where relatively clean fracture surfaces suggested a direct correlation to the earthquake. This was true from both a structural perspective and with regard to the potential for continued rainwater penetration into the monument. While not constituting a structural hazard, the structural behavior of the pyramidion's exterior stone panels—particularly in areas where planar displacement of the panel along one or both sides of cracks almost certainly occurred as a result of the earthquake—was, and remains, particularly interesting. In several locations these cracks were found to extend directly adjacent to or through the body of the stone "knuckles," or haunches, originally hewn from the inboard surface of each exterior stone panel. Movement associated with the earthquake also resulted in cracking through the corresponding stone teeth that extend from the leading edge, or tip, of each stone rib into the underside of each stone haunch.

To address these and related conditions inside the pyramidion, we worked closely with the NPS to explore a handful of temporary stabilization options that would allow the monument to be reopened on an interim basis until the design and implementation of long-term repairs could be completed. However, it was determined that the design and construction effort associated with that undertaking would very likely delay the start of the more critical long-term repairs. Moreover, the remobilization that would be required for the disassembly, along with the disposal of temporary stabilization materials, would result in added costs to the project. Acting out of caution and with an eye toward the successful completion of the long-term repairs necessary to expedite the reopening of the monument, the NPS determined that the monument would remain closed to the general public until the long-term repairs were complete.

Temporary measures to repel rainwater penetration—particularly at the pyramidion level—also were a concern but would require the return of our DAT and the use of materials and methods that would be easy to safely and effectively install using rope access. The work would also be reversible and would minimize the potential for damaging or contaminating the stone surfaces and substrates in a way that would negatively affect the long-term repair and preservation of the monument. After research and laboratory

Una Gilmartin's Account

AS AN ENGINEER WITH THE GOOD fortune to design repairs and retrofits for a number of structures recognized in the National Historic Landmarks Program, I never cease to be amazed by the incredible talent and ingenuity of those responsible for their original construction. The brilliance of their engineering is plainly revealed when you study their construction drawings and survey the cramped utility spaces where the skeleton of the structure is usually left exposed. Whether it is the Cellhouse on Alcatraz Island, in San Francisco Bay, or Perry's Victory and International Peace Memorial, in Put-in-Bay, Ohio, these structures remain a vibrant and tangible link to those who designed and constructed them so long ago. The brilliance of their design is rarely, if ever, overshadowed by the vulnerabilities of the structure that are sometimes revealed with a century or more of use or—in the case of an earthquake—within seconds.

While those on the East Coast felt the jolt of the Mineral, Virginia, earthquake on August 23, 2011, a small group of us engaged in the practice of earthquake damage assessment on the West Coast were touched by it a day later when we received a request to go to Washington, D.C., at 11 AM and boarded a plane at 3 PM. The next morning arrived earlier than expected and with it the knowledge that I would be one member of a team of engineers who would be assessing the Washington Monument and the Lincoln Memorial. As is typical for assessments, we met with the client and gathered as much information as was available on the degree of damage, and then we set out for the site. "Ask the structure" is a phrase coined by Jack Janney, one of the founders of Wiss, Janney, Elstner Associates, Inc. (WJE), and I find that nowhere does this statement hold more true than in our earthquake damage investigations. The Washington Monument had much to tell us that day and in the days and weeks that followed. One of our first lessons was that the elevator counterweights had been displaced from their normal position and that we would be climbing the 897 steps to the observation deck level. On the way up the 500 ft vertical shaft portion of the monument, we were treated to glimpses of the 192 commemorative stones— ornately carved stones set into the interior walls that flank the stair—donated by all manner of private individuals, organizations, cities, states, and other nations to provide a funding source for the original construction.

One basic element of a good earthquake damage investigation is to truly understand what damage is the result of the particular earthquake event in question, versus damage from other earthquakes or other sources entirely. When faced with earthquake damage, there can be a sort of human bias to ascribe the damage to the earthquake event that just occurred. For structures in zones of high seismicity, such as adobes in California, it bears remembering that in their two centuries of service many of them have experienced seismic events far in excess of those that we may have been dispatched to assess. Understanding what damage was a direct result of the August 23 earthquake was not particularly difficult for the Washington Monument, since it had not experienced damage from previous earthquakes and because new cracking to the marble and other stone surfaces could be clearly discerned through close observation.

The Washington Monument had much to tell us that day and in the days and weeks that followed.

Through our examination of the structure itself, it was clear that Lieutenant Colonel Thomas L. Casey, the engineer responsible for the design of the Washington Monument, was an extraordinarily talented individual. The geometry of the Casey-designed marble pyramidion alone is an engineering marvel. Nonetheless, we discovered that marble panels that form the exterior surfaces of the pyramidion developed through-thickness earthquake-related cracks. We also learned that portions of the marble rib units that serve as bearing surfaces for the support of the exterior marble panels had experienced cracking. As we crawled through the dusty and cramped space between the elevator roof level and the marble cruciform stone unit, we discovered spalling of this unit and cracking of a number of the tie beams. Other stone units and the lightning protection system experienced displacements. Damage also occurred below the pyramidion level, including much damage to the mortar joints to the shaft of the monument that would be a significant source of water penetration.

On the basis of our initial fieldwork and photographs of the exterior taken by helicopter, we knew that there was a high likelihood that there would be loose stone debris on the exterior of the monument. Our WJE colleagues with the Difficult Access Team rose to the challenge of performing limited stone removal and an exterior assessment of the monument. Through their efforts, the structure revealed even more information useful to the design of repairs in the months to come.

Repairing damage to a structure recognized in the National Historic Landmarks Program requires exercising a degree of restraint that can be challenging. Structures such as the Washington Monument are a product of their time, not ours, and need to remain so to the fullest extent possible. If the earthquake is a strong one, chances are it will expose vulnerabilities, whether in the design, the construction, or the materials themselves. Key to a good repair is understanding why the structure behaved the way it did under the given loading scenario. What beneficial behaviors did the structure exhibit and why? What fractured or displaced and why? Based on the era of design, what did the designers know and anticipate for loading and how does that compare to the loading we consider presently or the loading to which it may be subjected in the future? Ideally, repairs should continue to allow the structure to exhibit its best properties unimpeded but should address the exposed vulnerabilities.

Structures such as the Washington Monument are a product of their time, not ours, and need to remain so to the fullest extent possible.

Many factors were considered in the selection of repairs for damage to the Washington Monument. Structurally, we wanted to maintain consistency with existing load paths yet prevent loss of support under expected seismic demands. Visibility of potential repairs from both the exterior and the interior was carefully considered. Since repairs on the exterior can be difficult to maintain from a water intrusion perspective on a very tall structure—and since exterior repairs using stone dutchmen installed in a geometric pattern can be discerned by the human eye, even at great heights—repairs that could be executed from the interior were used when possible. For historic structures, it is important to view one's own repair as an intervention, perhaps even an unwelcome intrusion into the fabric of that structure, and to try to limit that intrusion. For this reason, and counterintuitive to many engineers, the potential reversibility of alternate repair details also was a consideration in the design of repairs. Ease of installation, risk of damage to the existing structure during installation, long-term durability, cost, consistency of appearance with the historic appearance, and the historic materials to which they would be fastened also were factored into the decision making during the course of designing repairs.

In the course of designing repairs to the Washington Monument, beyond the collections in Washington, D.C., we consulted the Casey papers at Historic New England. There we found a wealth of information on the design and construction of the monument. My personal favorite is a letter stating the names of "stonemasons working on the Washington Monument that are not fast." This page, inked in flawless penmanship, states the names of those who worked at a slower pace. The second column lists the reasons, which include the comments "young" and "old and infirm." When I reflect on the monument, not only do I think of the leadership of George Washington and the brilliance of Casey, but I am reminded of the labors of very young and very old stonemasons whose efforts have left us one of the most exceptional structures in the world.

Una M. Gilmartin, P.E., is an associate principal in the San Francisco office of Wiss, Janney, Elstner Associates, Inc.

testing revealed several options available to us to temporarily fill cracks and joints in the exterior—including the use of expanding foam joint fillers and sealant specifically formulated to minimize the risk for plasticizer migration into the surrounding stone—we summarized our findings for the NPS and chose to simply install oversized, closed-cell backer rod into those joints and cracks to reduce, though not eliminate, the risk for rainwater penetration until long-term repairs could be completed. Our DAT returned to the monument for the weatherization the week of November 14.

Erik C. Sohn, P.E., M.ASCE, works on the west face of the monument.

COLIN WINTERBOTTOM (WWW.COLINWINTERBOTTOM.COM) AND MATTHEW GIRARD (WWW.MATTHEW-GIRARD.COM)
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WHEN WE BEGAN DEVELOPING the drawings and technical specifications that would guide the long-term repairs and preservation of the monument, we recognized several challenges that would have to be overcome. The first was related to schedule. In order to expedite the reopening of the monument to the general public, it was critical that we develop a game plan that would allow our multidisciplinary team of architects, engineers, and conservators to collaborate with management and technical staff at the NPS. The initial goal was for competitive bidding and contract award to be scheduled so that work could begin on-site in the fall of 2012. To realize that goal, we worked closely with the NPS to establish a timeline for completion that included a series of milestone meetings and teleconferences—both internally among the members of our design team and with representatives of the NPS—to share our ideas regarding the various long-term repairs and preservation treatments available for use on the monument, as well as to ensure that the engineering team at the NPS was fully aware of our progress and in a position to offer its input at regular intervals throughout the design phase of the project.

One measure implemented by the NPS to expedite the work was to organize—at the "50 percent submission" stage—a two-day meeting, design charette, and "page turn" with our team of architects, engineers, and conservators. That meeting, during which we rolled up our sleeves with the NPS architects, engineers, conservators, preservation specialists, and those responsible for the day-to-day operation and maintenance of the monument, may have been more productive than any other single event during the design phase of the project. In addition to vetting the various repair options that we had begun to develop, this approach also allowed us to discuss in real time and with minimal delay in our progress related issues that would be impacted by the work, including site access and security; removal and reinstallation or replacement of the existing lightning protection system; removal and reinstallation or replacement of the existing interior glass panels and related finishes at the 490 and 500 ft observation deck levels to permit repair of interior stone surfaces; cataloging, removing, storing, and reinstalling the existing outdoor stone pavers, benches, flagpoles, and lighting necessary to accommodate the potential placement of concrete footings and pipe scaffolding to complete the work; and landscape protection and coordination with ongoing construction activities at the adjacent National Museum of African American History and Culture. The design phase of our work began with a kick-off meeting with the NPS in Washington, D.C., on December 15, 2011, and was completed with submission of our final construction documents on June 27, 2012.

The primary mandate from the NPS was to develop a repair design that would restore the monument to the condition that existed prior to the earthquake. However, the NPS was also interested in considering structural improvements if they were needed to protect the monument during future seismic events. Consequently, a detailed analysis of the structure's response to the earthquake of August 23 was performed in order to understand the correlation between movement induced by the event and the location, nature, and extent of resulting damage. Estimates of future seismic risk also were made. This work was led by Terrence F. "Terry" Paret, M.ASCE, from our San Francisco office. Using computer modeling techniques and software developed specifically to simulate seismically induced movement in buildings and structures, models were developed to simulate relevant features of the monument and the supporting soils. The models were then subjected to synthetic representations of shaking derived, in part, from data associated with the actual seismic event. The models were calibrated by comparing the results of those analyses with the physical damage sustained by the monument. After the models were validated, the effects of possible future earthquakes were estimated by subjecting the models to mathematical representations of postulated events. This general analytical approach was validated independently by the members of the team from Tipping Mar, who conducted independent analyses using different analytical models and different analysis software. There was wide-ranging agreement between the two disparate modeling approaches. (The environment and infrastructure division of the British firm AMEC plc conducted the geotechnical and seismological studies utilized by the structural analyses.)

- When the monument is subjected to ground shaking during an earthquake, it, like all other structures, responds by swaying. That swaying causes deformation of the pyramidion, the shaft, and/or the soils beneath the foundation to occur to varying degrees, depending on certain subtle characteristics of the shaking during different earthquake events. In other words, some earthquake events from some sources may excite the pyramidion relatively more than the shaft and base of the monument, but other events may excite the shaft and base more than the pyramidion.
- The ground shaking at the National Mall during the August 23 seismic event caused a substantial amount of deformation to the pyramidion and to the top of the shaft just below the pyramidion. However, it brought relatively little deformation to the lower portions of the shaft and to the soils beneath the foundation.
- The type of damage experienced by the pyramidion and the top of the shaft during the August 23 seismic event can be predicted reasonably well using the now-understood characteristics of the shaking on the National Mall on August 23 and the models developed during this seismic assessment.
- The pyramidion was found to be a particularly vulnerable element, primarily because the soil surrounding the monument can transmit and even amplify the types of vibrations that tend to excite the upper portions of the structure. In engineering terms, the monument's modes of vibration that result in the greatest forces and deformations of the pyramidion are particularly prone to excitation by the types of ground motions imported by the surrounding soils.
- The occurrence of another earthquake capable of causing damage to the pyramidion similar to what occurred in the August 23 event is judged to be extremely unlikely. This finding is based on the unusually high energy content of this earthquake in the period range of the supporting soils and the pyramidion. With respect to the particular shaking characteristics to which the pyramidion is most vulnerable, the ground motion at the National Mall during the August 23 event was roughly 10 to 20 percent more severe than the predicted median 2,475-year event. In other words, the pyramidion performed reasonably well under the demands of a seismic event that occurs on average less than once every 2,475 years, and a future 2,475-year event is likely to cause similar or less damage to the pyramidion than the damage that occurred during the August 23 event.
- Because of the inherent variability in the many parameters used to quantify earthquake-generated shaking, the expected damage patterns are not the same for events with identical return periods. Therefore, certain stone masonry units and joints in the pyramidion that were not damaged during the August 23 event could be damaged in a future event of similar return period. The overall severity of damage in a future 2,475-year event, however, would not be expected to be as severe as the damage sustained during the August 23 event.
- Ground shaking that primarily affects the monument's shaft would probably come from a source more distant than the source of the August 23 event. The magnitude 7.5 earthquake centered near Charleston, South Carolina, that occurred in 1886 is believed to have generated shaking intensity at the National Mall that is consistent with or exceeds the 2,475-year hazard.
- The simulations run with the computer models being subjected to 2,475-year earthquake motions from a more distant source indicate that the shaft of the monument and the soils that support it can withstand a 2,475-year earthquake without major damage. Some cracking of mortar joints and perhaps minor spreading of some masonry could occur, but damage to or instability of competent stone masonry units would not be expected. It should be noted, however, that a number of stone masonry units in the shaft have deteriorated over the years, and some have repairs that are failing. These locations would be susceptible to damage during future seismic events of various magnitudes.
- The finding that the structure of the shaft and the soils supporting the base of the monument are adequate to withstand a distant 2,475-year event is supported by the historical record. Construction of the monument was completed in 1884, and historical records accessed during this project do not mention any damage occurring during the 1886 Charleston earthquake.

Although the members of our seismic team completed their work on a track parallel to the efforts of our repair design team, they were functionally embedded with the individual members of our repair design team on the West Coast and therefore in position to immediately and substantively inform the design process. This was particularly true with regard to detailing associated with the in situ stabilization of the damaged portions of the unreinforced stone structure and related elements that support the exterior stone cladding at the pyramidion. While the mandate from the NPS was to restore the monument to the condition that existed prior to the earthquake, the challenge now was to develop stabilization details and treatment strategies that were both responsive to the findings of our seismic team and sensitive to the historic fabric of the monument.

Because the pyramidion is subject to damage during a future seismic event, careful consideration was first given to whether remediation designed specifically to address the potential for future damage was necessary in order to conform to commonly invoked seismic safety expectations. These expectations, briefly described, are that the primary goal of seismically resistant design is to protect the lives of occupants. The occurrence of some structural and nonstructural damage during a major earthquake is acceptable, and such damage may or may not be repairable. While the pyramidion may well experience some level of damage during a future 2,475-year earthquake, the reoccurrence of damage at a level that could reasonably be considered consistent with the damage documented after the August 23 event—an earthquake with an estimated return period of between 2,000 and 3,000 years—is relatively remote. Moreover, seismic safety standards employed nationally for new construction require structures to satisfy life safety criteria for a so-called design earthquake, which is equivalent to only two-thirds of the predicted 2,475-year event. In accordance with this industry standard definition, a design earthquake would cause substantially less damage to the pyramidion than what occurred in the August 23 earthquake. Seismic improvements to the pyramidion are therefore not needed to conform to the seismic safety standards that are applicable to most other public and privately owned properties in the United States.

That said, the existing panel-to-rib connections not damaged during the August 23 seismic event and therefore not currently scheduled for repair as part of the long-term repairs and preservation of the monument will remain at some risk for damage during a future very strong, but rare, seismic event. Although the degree of risk is difficult to quantify, in part because different earthquakes have the potential to damage different panel-to-rib connections, the possibility that a percentage of these panels could become dislodged during a future seismic event cannot be discounted entirely and was therefore given further consideration. The panel-to-rib connections at which two panels are supported, as well as those located in the course just below the stone tie beams inside the pyramidion, were found to be particularly vulnerable during our analysis, and both sustained damage at a far greater rate after the August 23 seismic event than the panel-to-rib connections at which only a single panel was supported at the exterior surface of the pyramidion. In response to this finding, two-panel connections not damaged as a result of the August 23 earthquake are being supplemented. In addition, detailing and treatment strategies intended to address connections directly adjacent to those panel-to-rib connections that were damaged by the August 23 earthquake were developed to address the fact that redistribution of some gravity loading occurred wherever connections sustained damage.

Our assessment also found that the shaft and the soils supporting the monument are not vulnerable to safety-compromising damage from a 2,475-year event, and as such, seismic strengthening measures are not needed to conform to the seismic safety standards that are applicable to other public and privately owned properties in the United States. Structurally significant permanent deformations are expected in neither the shaft nor the soils, although minor cracking of mortar joints and minor but localized spreading of the masonry in the shaft may occur.

MUCH HAS BEEN WRITTEN regarding the various types of marble, granite, and gneiss that form the vast majority of the Washington Monument. Foremost among those authors is George P. Merrill, an American geologist who was a graduate of the University of Maine and served as the assistant curator and then head curator of the geology department at the National Museum (now the Smithsonian Institution) beginning in 1881. He was also a professor of geology and mineralogy at the Corcoran Scientific School of the Columbian College in the District of Columbia (now George Washington University) from 1893 to 1916. While it would be impossible within the context of this article to cover all that Merrill has written regarding the geological significance of the various stones used to construct the Washington Monument and other historic landmarks throughout Washington, D.C., we know from his writings and from the work of other authors who cite his work that the first 152 ft or so of the monument (1848–54) consists of an exterior layer of marble extracted from a geological formation in Texas, Maryland, that extends through Cockeysville, Maryland (both near Baltimore), the same region that supplied the marble visible today on the upper 390 ft or so of the monument (1879–84). At the lower sections of the monument, we also know that the exterior marble cladding was set over an interior layer consisting largely of bluestone gneiss, a stone supplied locally at the time by the nearby Potomac River quarries, and a material that is geologically similar to granite and was also used to construct the foundation of the monument.

Setting aside the bluestone gneiss, where no significant damage apart from open mortar joints was observed as a result of the earthquake, and the four courses of exterior marble immediately above the 152 ft level that were supplied by the Lee quarry, in Massachusetts, our focus during the design phase of the project was to gain a better understanding of the fundamental geology and material characteristics of the marble supplied from quarries that once operated in the Cockeysville region of Maryland. The reasons for this were threefold. First, the marble from that region sustained more damage than any other type of stone on the structure. Second, that particular marble represents a potential source of repair material. And finally, the stored material ("attic stock") that was not used as part of the 2000 campaign and remains in the possession of the NPS reportedly originated from this region.

One of the more interesting facts that emerged from our research regarding the geological formation that extends through both the Cockeysville and Texas, Maryland, regions is the large range of stone present in that formation that contains both very pure calcite as well as dolomite, the latter considered harder and denser than calcite and, therefore, more suitable for use in the construction and building product industries. In addition, the crystal size of the stone available from that formation ranges from fine-grained stone to stone that is medium to coarse grained. We noted visible variations in both color and texture in the currently active quarry as one moves vertically through the formation.

While mineralogical differences were not immediately evident during our rope-access survey and assessment of the monument exterior, the medium-to-coarse texture of the stone and the presence of copper-colored mica in horizontal bands, or veins, that extend through the body of the marble used in the stone courses located at and immediately below the pyramidion are consistent with the description of the stone originally quarried from this region. In fact, while many of the cracks observed in the days and weeks immediately following the earthquake that (based on the relatively clean fracture surfaces associated with those cracks) could reasonably be attributed to that event consisted of edge-to-edge "corner," or shear, cracking that extended across veins in the marble, several other loosened sections of stone were removed from areas where failure occurred along the (inherently weaker) veins in the marble. The two largest stone fragments removed from the east face of the monument fell into this latter category.

The Cockeysville, Maryland, quarry that supplied the stone for the monument has been filled with water and is now used for recreational purposes. However, a relatively small amount of marble extracted from the same geological formation and reportedly set aside as waste has been located in a nearby quarry and, together with the stored material already in the possession of the NPS, may hold some promise for use as dutchman units. The stone available at the operating quarry appears to include the range of marble present on the monument. Further analysis of that material, particularly with regard to the potential presence of microfractures resulting from the blasting techniques used during extraction, will be completed to determine its suitability for use in this application.

We are reminded of the trust that has been placed in us to help preserve and protect one of the most visible and historically important landmarks in the United States.

THE IMPLEMENTATION of long-term repairs and preservation measures began with a preconstruction meeting at the end of October 2012, followed by the establishment of an expanded security perimeter and initial mobilization at the jobsite by the NPS and the construction team. After a secure jobsite perimeter has been established, work will begin in preparation of the erection of full-height pipe scaffolding. The scaffolding will be substantially the same in overall shape and configuration as that used to access the exterior surfaces of the monument during the 2000 repair campaign. To the extent feasible (or otherwise prudent from an engineering perspective), it may include many of the components that were designed and fabricated expressly to accommodate and reflect the overall profile of the monument as a stone obelisk during the 2000 repair campaign. Swing staging will again operate within the scaffolding to provide vertical access to the exterior stone surfaces below the pyramidion, with working platforms added to the design at the pyramidion level to facilitate the more challenging repairs that will be required in that area. **CE**

Daniel J. Lemieux, AIA, R.A., M.ASCE, is the principal and unit manager in the Washington, D.C., office of Wiss, Janney, Elstner Associates, Inc. (WJE), and served as the architect of record and project manager for the postearthquake assessment, stabilization, and repair design of the Washington Monument on behalf of WJE. Terrence F. Paret, M.ASCE, is the senior principal in the San Francisco office of WJE and managed the seismic vulnerability assessment of the monument.

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