OR CENTURIES, the site believed by Christians to be the tomb in which Jesus of Nazareth was placed following crucifixion has intrigued religious pilgrims, historians, and scientists. Hewn from the rock at the area known as Golgotha, outside the old city of Jerusalem, the Holy Tomb of Christ, as it is known, has evolved from a burial chamber to a complex aedicule structure surrounding and embedding remnants of the original monolithic tomb.

Known as the Holy Aedicule, the structure is a small, stone-clad masonry building that is located within another building—in this case, the Church of the Resurrection, also known as the Church of the Holy Sepulchre, which was constructed in Jerusalem in AD 326. The Roman emperor Constantine the Great, working with his mother, now known as Saint Helena, is credited with excavating much of the tomb and constructing the original aedicule as well as the church building around it. Over the centuries, the aedicule has sustained considerable damage and deformation. It has also undergone many attempts at reconstruction and interventions designed to restore the site’s structural integrity. The most recent attempt at restoration was completed in 1810 by the architect known as Komnenos. Since that effort, however, this unique monument has experienced significant additional damage and deformation, which demanded immediate interventions to reinstate its structural integrity and ensure its sustainable preservation. The deformations of the Holy Aedicule, for example, had reached a dangerous-enough point during the first half of the 20th century that an iron frame was installed around the


Before the recent rehabilitation project, the structure known as the Holy Aedicule, believed to house the tomb in which Jesus of Nazareth was placed after crucifixion, was supported by an iron frame installed in 1947. That frame was removed during the rehabilitation.
structure in 1947 to help prevent a collapse. This was during the period of the British Mandate when Great Britain administered the region from 1922 to 1948. The frame represented only a temporary solution, and since then the situation had grown worse, as evidenced by the additional building of the aedicule’s stone facade and the structure’s generally poor state of preservation.

The Holy Tomb of Christ is controlled by three distinct Christian groups—the Greek Orthodox Patriarchate of Jerusalem; the Franciscan Order of the Roman Catholic Church, known as the Custody of the Holy Land; and the Armenian Patriarchate of Jerusalem. Together, these groups are designated the three Christian communities, and though they have sometimes sparred—a physical altercation broke out inside the Church of the Resurrection in 2008—they managed to put aside their differences during a recent project designed to rehabilitate the site. This rehabilitation effort began when the National Technical University of Athens (NTUA) was invited to implement an integrated diagnostic research project and strategic planning effort to determine the materials and interventions that would be necessary for the conservation and rehabilitation of the Holy Aedicule.

Because of the complexity of the structure and the lack of appropriate engineering information, the study was conducted through an interdisciplinary approach with innovative technologies and an emphasis on nondestructive testing and integrated documentation.

Specifically, the NTUA team used infrared thermography and portable digital microscopy to assess the state of the exterior and interior stone facings. In parallel, the team also used analytical testing of core samples to characterize the building materials—the mortars and stones—and to detect any evidence of decay. This work combined optical and digital microscopy, scanning electron microscopy coupled with microanalysis, thermal analysis, X-ray diffraction, microwave intrusion, petrographic tests, and mechanical tests. The results of these tests identified the mortars that support the site’s masonry as the critical material and the deterioration of these mortars as the main factor causing the deformations of the aedicule.

The historical mortars used in the aedicule were characterized as slightly hydraulic lime mortars and mixed lime–gypsum mortars and presented high percentages of soluble salts; indeed, the soluble salt levels were found to be extremely high, which indicated that the masonry was in danger of experiencing swelling and salt-induced degradation. Using a reverse-engineering approach, the NTUA team analyzed the historical mortars—in combination with the characteristics of the masonry stones and the prevailing decay factors—and determined that the damaged mortars had to be replaced with a compatible and “performing” restoration mortar; the term “performing” refers to the structural performance of the mortar and its mechanical properties and/or physicochemical performance and durability.

The properties of the restoration mortar that the team selected were assessed by a finite element model of the structure to verify the new material’s structural performance before its application. Furthermore, because the aedicule features different layers of material that could not be completely dismantled, the team also determined that it was necessary to apply compatible and performing grouts, along with the new mortars, to strengthen and homogenize the various layers from different construction phases of the monument. The volume of the mortars and grouts necessary to rehabilitate the aedicule was estimated through the volumetric information extracted from a 3-D geometric model.

This 3-D model of the Holy Aedicule was created using image-based techniques and terrestrial laser scanning. The production of the high-resolution model enabled the team to extract the necessary conventional 3-D information. For example, highly accurate specific geodetic measurements were correlated for all areas within the Rotunda—the large, circular space within the western end of the Church of the Resurrection, at the center of which is located the Holy Aedicule—-to determine how much the columns of the aedicule had deviated from vertical. Additionally, a combined study involving ground-penetrating radar and architectural analysis was performed to reveal the internal layers of the aedicule and to determine the different construction phases.

The complexity of the aedicule and the limited accessibility the team had to examine its surfaces with ground-penetrating radar, a 2-D approach was used to inspect the aedicule’s internal layers. Specifically, a series of layer-by-layer scans was correlated with information from architectural analysis and historical documentation to provide contours representing the internal interfaces corresponding to the main layers. This analysis also identified the presence of remnants of what is known as the Holy Rock—parts of the original burial chamber that are now embedded within the current aedicule structure—as well as the primary masonry, filling mortar, and stone facades. These georeferenced contours were then integrated to create a 3-D model of the two blocks of the remnants of the Holy Rock, embedded within the western part of the aedicule.

The aedicule was examined under both static and seismic loads via elaborate finite element modeling and analysis. The bearing structure of the Holy Aedicule was assessed in terms of the seismic forces that might threaten its structural integrity as well as the static loads from its constituent materials. The seismic forces were based on the historical seismicity of Jerusalem, according to the current provisions of Eurocode 8 and the available, international scientific literature. According to the seismic hazard map of Israel, a peak ground acceleration of 0.13 g accounts for rock conditions in Jerusalem. This peak ground acceleration would have a 10 percent probability of being exceeded in 50 years.

To calculate the acceleration spectrum, the provisions of the current Eurocode 8 were applied for a Type 1 design earthquake spectrum—meaning, for regions of high or moderate seismicity—a maximum value of 1.4 as the “importance factor,” which puts the site on par with hospitals, power plants, and police stations for protection during the period following an earthquake. The numerical analysis provided the contours of maximum principal stresses for the main bearing body of the structure before the interventions. The analysis also revealed significant cracks in the internal vaults of the aedicule, at the wall that separates two chambers within the structure, and in the area of the internal stairwells where the thickness of the masonry is reduced.

Based on the findings of the NTUA study, a series of interventions was planned, including restoration mortars and grouts, as well as various new reinforcement systems. When these proposed materials and interventions were incorporated into a modified finite element model of the aedicule, it became clear to the team that the proposed rehabilitation would provide adequate strength and reinstate the monument’s structural integrity.

A historic agreement—known as the Common Agreement—was signed on March 22, 2016, between the three Christian communities to implement the project, and contributions of 3.7 million euros (U.S. $4.3 million) were raised from sources all over the world to fund the effort. Especially noteworthy were contributions from two trustees of the New York City-based World Monuments Fund—Mia Conference A 2017 Civil Engineering NOVEMBER 2017 56

Section of the 3-D Model of the Holy Aedicule Before Rehabilitation

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Ertugrul and Jack Shear—and donations from Aegean Airlines. An interdisciplinary team from the NTUA was formed and included representatives of the university’s schools of chemical engineering, architectural engineering, civil and surveying engineering, and civil engineering. Restoration and conservation working teams were then selected on the basis of the members’ expertise in the restoration of important Byzantine monuments and the Acropolis of Athens. Two of the conservators were employees of the Greek Ministry of Culture. A conservation laboratory and an interdisciplinary documentation and monitoring laboratory were established at the site to support the overall project.

The importance of the monument, the complexity of the project, and the site’s historical and religious significance—in particular, the need to preserve the Holy Rock—meant that the organization of the worksite and the scheduling of the timetable had to accommodate various restrictions and engineering challenges. Moreover, the site had to remain accessible to pilgrims and those engaged in the performance of religious functions. In combination with safety requirements, this meant that most of the work had to be accomplished at night. Finally, a strict deadline was set to complete the rehabilitation work within 12 months after the signature of the Common Agreement to make sure that Easter celebrations could be held at the rehabilitated Holy Aedicule.

To protect the pilgrims and other visitors at the site, the work areas were concentrated on the north and south sides of the aedicule, creating a corridor to the interior of the monument that was separated from the rest of the Rotunda by metal panels. A conservation laboratory in the Latin Gallery, which is located on an upper floor of the church to the northeast of the aedicule, was built. The conservation laboratory was established in 1947 at the north and south facades was examined via another finite element model, which indicated that the framing could not be used as a retaining wall during the repositioning of the aedicule’s stone cladding. Instead, the frames were further supported and pinned at the base, and the existing steel rods connecting them at the top were retained. The structural analysis of the frame also revealed the use of diagonal, wide-flange steel HEB 200 beams to strengthen the structure, which was then able to be used as a retaining wall. The British engineers had not installed a frame on the east or west facades, a new frame was designed and installed to support those sides of the aedicule. Because of the configuration of the front facade of the aedicule and the fact that the monument had to remain open to pilgrims, four vertical HEB 200 beams were fixed to the rock foundation and functioned as cantilever supports.

The stone tiles of the Rotunda were covered with a false flooring of concrete plates, which, in addition to protecting the stones, also provided even ground for the work equipment. Special crane systems were designed and manufactured to dismantle the stone facades of the aedicule, and access to the exterior surfaces at elevated portions of the structure was provided through a mobile elevation platform and the installation of temporary scaffolding. Two wooden lofts were constructed to provide access to key areas of the aedicule. One was installed inside the aedicule structure itself, directly above the tomb to protect the tomb and the pilgrims who might be there during the interior rehabilitation work. This loft also provided access to an important painting on the wall of the tomb chamber as well as to the interior of the chamber’s dome. A second loft was constructed in the Chapel of the Angel, which is the antechamber of the aedicule, to provide access to the chapel’s dome for rehabilitation interventions. Additional measures were taken as the rehabilitation work progressed.

The rehabilitation process began with the dismantling and removal of the stone panels that form the exterior facade. Dismantling took place only in select areas, not across the entire aedicule, because the deformations had been observed only at the middle to lower parts of the overall structure. Each stone slab was fully documented, including by 3-D laser scanning, and transferred to the conservation laboratory to carry out cleaning and preservation interventions. The structural integrity of the remaining cladding had to be ensured following the removal of the lower panels. As a result, the aedicule’s arches were supported with timber elements and scaffolding. Behind the stone panels, the damaged filling mortar was removed, the inner rubble-type masonry of the structure was revealed, and the joints were cleaned. A compatible and performing restoration material and method during the study, was applied to restore the masonry.

Unfortunately, some parts of the masonry—mainly corresponding to the areas around the tomb chamber—were in such a poor state of preservation that reconstruction was required to ensure the aedicule’s structural integrity. The existing, low-strength masonry was removed, in some cases up to a height of 2 m and to a depth that varied depending on the curvature of the remnants of the Holy Rock. During the existing retaining system was designed to work with the existing frame, imposing upward vertical loads to avoid collapse of the upper part of the wall. Part of the original masonry was also removed in such a way to form an arch, which was then filled with the reconstructed masonry.

The dislocated columns inside the aedicule as well as on the external facade were reset, the external columns vertically realigned using actuators. The changes to the deviations from vertical were verified throughout all the phases of the work by comparing them to documented information.

The homogenization of the structural layers of the aedicule and the consolidation of the Holy Rock remnants were achieved by the injection of compatible and performing grouts. Geometric and architectural data facilitated the design and documented the grout injection tube design. The installation of the injection pipes created a matrix at different depths, based on sections of the geometric model and the results from the ground-penetrating radar analysis. Advanced nondestructive testing techniques were used to assess the effectiveness of the grouting materials and procedures, and an analysis of the grout volume distribution showed that grouting was successful in homogenizing the interface between the restoration masonry and the Holy Rock remnants.

The grouting was carried out in three zones along the height of the aedicule. The first zone began at the floor level and mowed up 1.5 m. The second zone measured from 1.5 m to 3 m of the height, reaching to the top of an arch. The third zone encompassed the uppermost portions of the aedicule facade, as well as the roof of the structure. Before the grouting work in the first zone—the Holy Tomb had been examined with ground-penetrating radar, ultrasonic tomography, and endoscopy—the three Christian communities decided that the tomb should be opened to protect its interior from any overflow of the gross material that would then solidify inside the tomb. To open the tomb involved lifting a large marble slab that was emplaced in the marble cladding around the tomb. Because this slab was already partially cut at the middle, it was quite probable that the marble would crack from the bending that could occur during the removal process. To avoid such damage, the slab was removed by sliding it open, like a drawer. The opening of the Holy Tomb of Christ, which was performed to control the grouting procedure, revealed the original rock surface on which Jesus’s body is believed to have been placed. During the grouting procedure this surface was protected from gross flow, which preserved the monument’s significance while also ensuring the longevity of the site. A window-like opening was also created in the interior wall opposite the tomb to control the grouting at the south interior area.
The grottoing of the second and third zones also had to be undertaken with considerable care so as to not damage the interior frescoes. The internal marble cladding of the aedicule is part of the load-bearing structure, and thus none of its members could be removed. The Coptic Chapel, however, which is a small, partially enclosed space framed in iron lattices, was relocated from the exterior wall of another section within the Rotunda. A series of iron rods that had been used in the construction of the aedicule had become partially oxidized, and in some locations had even completely disintegrated; consequently, the intervention aimed to preserve the remaining sections of the rock.

Following the strengthening of the main masonry, the external stone panels were re-assembled. The first step in this process involved curing the exterior stone panels that were then grouted and then grouted and subsequently coated. The cladding bars were chosen for their significant durability and high level of compatibility with the historical masonry. Being cylindrical with smooth surfaces, however, the bars were initially unsuitable for use as anchors. They were then passed through a deformor that created closely spaced ribs that differed from those of steel rebars in terms of distance and shape. While literature and standards exist that describe the bond created between steel rebars and concrete, titanium rebars were not applicable to these special-defomed titanium bars. Instead, a series of extensive pull-out tests were conducted on the proposed titanium bars. Grade 2 titanium bars were used in these bend tests, which demonstrated that the bars would neither rupture nor crack if used to anchor the stone cladding to the interior masonry wall. The cladding consists of two types of stone: a beige limestone from the quarry below and close to the foundations of the Aedicule and a pink hue and touches of beige. The limestone and a dolomitic limestone were dressed now, the net impact on the monument would have been negligible, and heightened. But the ultimate concern for the rehabilitation project was how to ensure that the problems posed by the aedicule would not be exacerbated. This was especially true at the south part of the Rotunda floor, which is closely correlated with the moisture transfer phenomena. The presence of slab was monitored through electrical resistivity tomography revealed an array of underground cisterns and channels beneath the Church of the Resurrection. Specifically, ground-penetrating radar and electrical resistivity tomography revealed an array of underground features, either natural or man-made and often interconnected with each other, that enabled the flow of moisture, potentially threatening the foundations of the aedicule. Indeed, the geomorphology of accessible under-ground areas—for example, the large cistern at the north side of the Rotunda floor as well as a channel connecting it to the aedicule—highlighted the importance of the water-drainage and moisture management within the church. By examining the history and the serious potential problems that could be caused by the resulting humidity. Various excavations around the aedicule, where remnants of structures dating to the Constantinian era have been discovered, highlighted the complexity of the surface morphology, especially beneath the Rotunda floor, which is closely correlated with the moisture transfer phenomena. This was especially true at the south part of the Rotunda floor, where an earlier excavation had revealed the existing underpinning to be highly corroded and the supporting materials to be in a state of intense deterioration. Clearly, this area had been affected by spray condensation, leakage, and moisture transfer. The close proximity of such areas to the aedicule necessitated also evaluated the addition of the transfer of moisture below and around the monument. This will be achieved through two interrelated approaches. The first approach, already adopted, involved the rehabilitation of the vaulting above the chamber and the chapel of the Angel. The second approach, involving the control of the moisture transfer-related damage that the structure had sustained before its rehabilitation and improved its durability against environmental factors. In addition to these interventions, a ventilation and dehumidification system was designed and installed in the outer wall of the aedicule. To remove the water vapor and controls the microclimatic conditions within the tomb chamber and the Chapel of the Angel, as well as the space behind a new observation window that was installed in the south part of the aedicule.

The future work planned for the site is of utmost importance to ensure the overall sustainability of the Holy Tomb of Christ and its surrounding structure. (Continued on Page 78)
Faithful Rehabilitation

(Continued from Page 61) The proposals and the related detailed studies for these additional efforts have been presented to the three Christian communities for their consideration. Because of the work completed so far, however, the Holy Tomb of Christ will continue for years to come as a living monument that speaks to all humanity, the engineering innovations that were employed serving only to amplify its voice.

The authors wish to acknowledge the leaders of the Christian communities: His Beatitude the Greek Orthodox Patriarch of Jerusalem Theophilos III; His Paternity Archbishop Pierbattista Pizzaballa, who was the Custos of the Holy Land until May 2016 and is now the Apostolic Administrator of the Latin Patriarchate of Jerusalem; Father Francesco Patton, who has been Custos of the Holy Land since June 2016; and His Beatitude the Armenian Patriarch of Jerusalem Nourhan Manougian. Acknowledgements are also attributed to the members of the Holy Sepulchre Common Technical Bureau: Theo Mitropoulos, Ph.D., the director of the Common Technical Bureau and construction site manager; Ousama Hamdan; Carla Benelli; and Irene Badalian.

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The National Geographic Society, in Washington, D.C., is hosting a new exhibit, “Tomb of Christ: The Church of the Holy Sepulchre Experience,” at its Washington-based museum. The exhibit is scheduled to open this month and run until August 15, 2018. Described as “an immersive 3-D experience,” the exhibit will enable visitors “to virtually visit the church and learn about its storied history and enduring mysteries,” explains the National Geographic website that discusses the exhibition: www.nationalgeographic.org/dc/exhibitions/tomb-of-christ.


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