FAITHFUL REHABILITATION

History, culture, religion, and engineering all intertwined in a recent project in Jerusalem to rehabilitate and strengthen the site believed to be the tomb of Jesus of Nazareth. Modern methods, including 3-D laser scanning, nondestructive testing techniques, and ground-penetrating radar, combined with careful documentation, revealed the secrets of how to help preserve and sustain the ancient site for future generations.

BY THE NATIONAL TECHNICAL UNIVERSITY OF ATHENS INTERDISCIPLINARY TEAM FOR THE PROTECTION OF MONUMENTS AND CONTRIBUTING AUTHORS

FOR 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 was expanded and altered in form.

Today, the Holy Aedicule and the Holy Tomb of Christ are not only a mystery to historians and a focal point to the faithful, but also represent important historical and cultural monuments that modern science was called upon to protect and preserve despite considerable engineering challenges. The engineering community was not called upon to resolve issues of faith, of course, but to provide solutions based on scientific methodologies, facts, and sound practices. Their efforts were intended to ensure the structural integrity and sustainability of the Holy Aedicule and to preserve and reveal the historical, cultural, and religious significance the structure represents.

Over the centuries, the Holy 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

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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.

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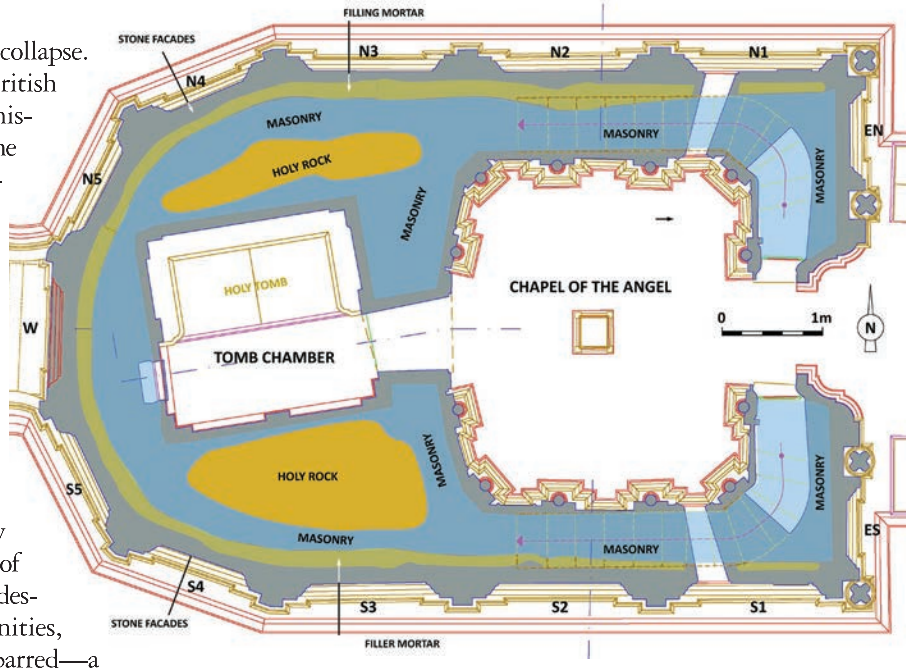


Plan View of the Holy Aedicule

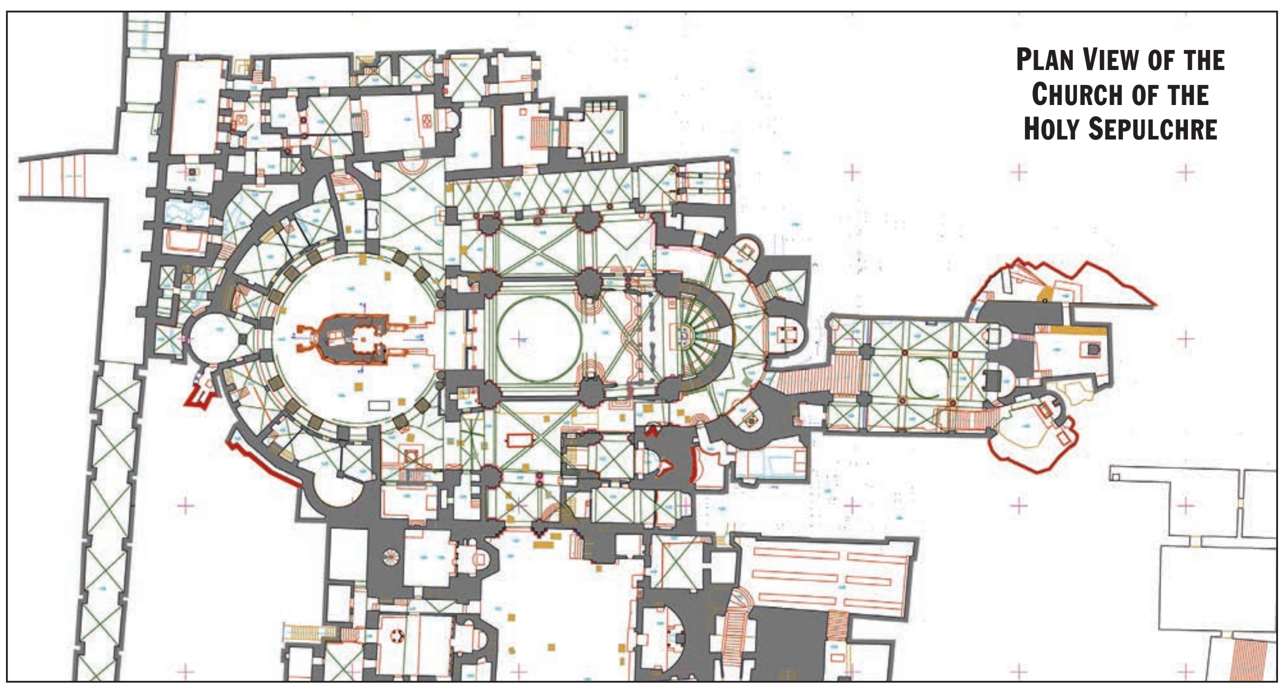
structure in 1947 to help prevent a collapse. This was during the period of the British Mandate when Great Britain administered the region from 1922 to 1948. The frame represented only a temporary solution, and since then the situation had grown worse, as evidenced by the additional buckling of the aedicule's 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, mercury intrusion porosimetry, total soluble salts 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.



Plan View of the Church of the Holy Sepulchre

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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 2-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.

Because of 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. The team 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 0.13g accounts for rock conditions in Jerusalem. This peak ground acceleration would have a 10 percent probability of being exceeded in 50 years.

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

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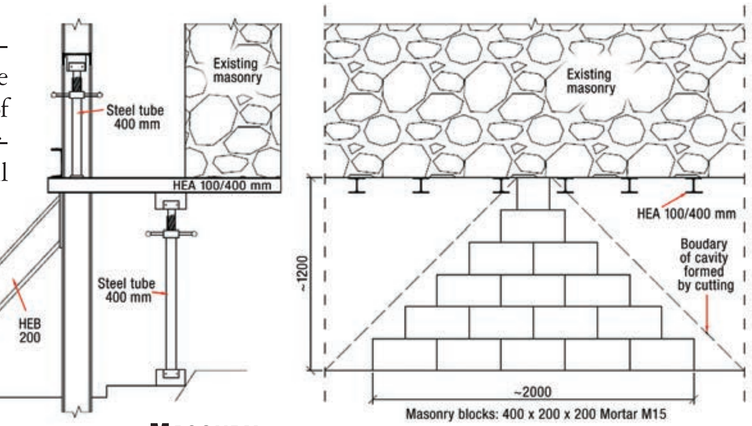
To calculate the acceleration spectrum, the provisions of the current *Eurocode 8* were applied for a Type 1 design earthquake spectrum—meaning, for regions of high or moderate seismicity—and a maximum value of 1.4 as the "importance factor," which puts the site on par with hospitals, power plants, and 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 at 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—Mica

Ertegun 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, architecture, rural 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.



MASONRY RETAINING SYSTEM

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.

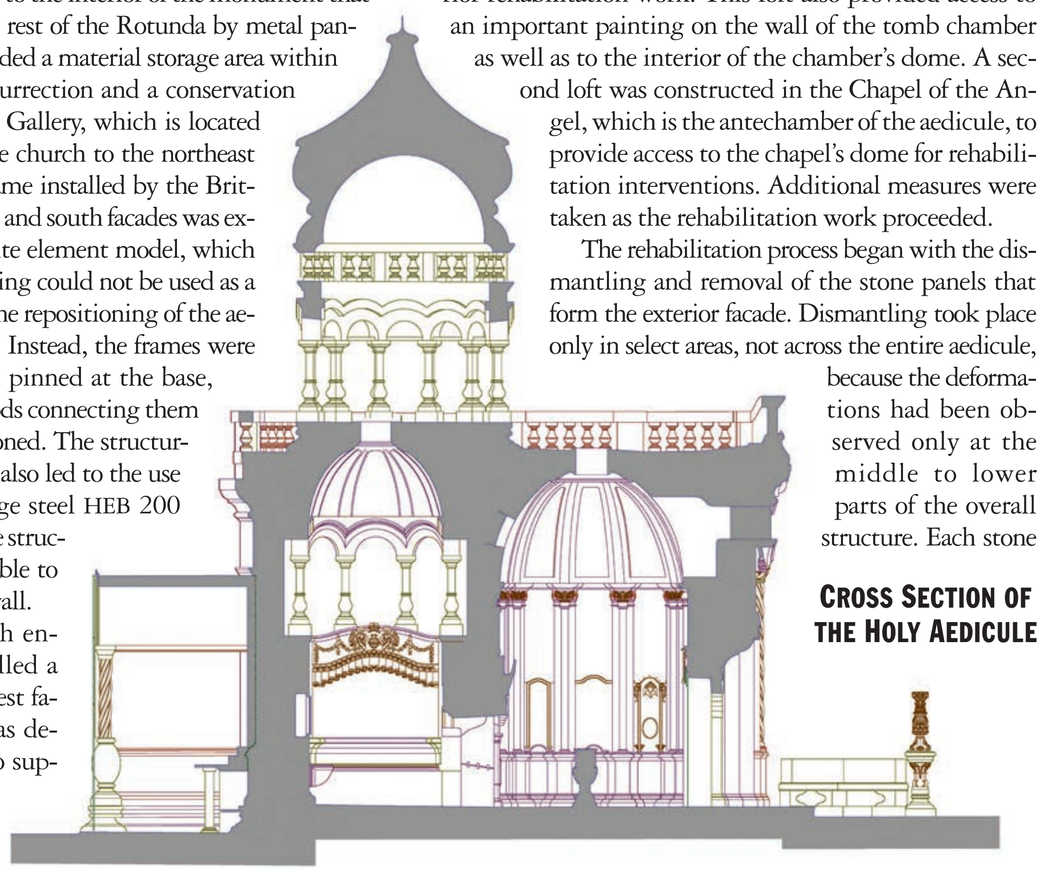
To protect the pilgrims and others at the site, the work areas were concentrated on the north and south sides of the aedicule, creating a corridor to the interior of the monument that was separated from the rest of the Rotunda by metal panels. The work site included a material storage area within the Church of the Resurrection and a conservation laboratory in the Latin Gallery, which is located on an upper floor of the church to the northeast of the aedicule. The frame installed by the British 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 retensioned. The structural analysis of the frame also led to 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.

Because 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 cantilevered 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 proceeded.

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 undergo cleaning and protection 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 disintegrated filling mortar was removed, the inner rubble-type masonry of the structure was revealed, and the joints were cleaned. A compatible and performing restoration mortar, as selected during the study, was applied to restore the masonry.



CROSS SECTION OF THE HOLY AEDICULE

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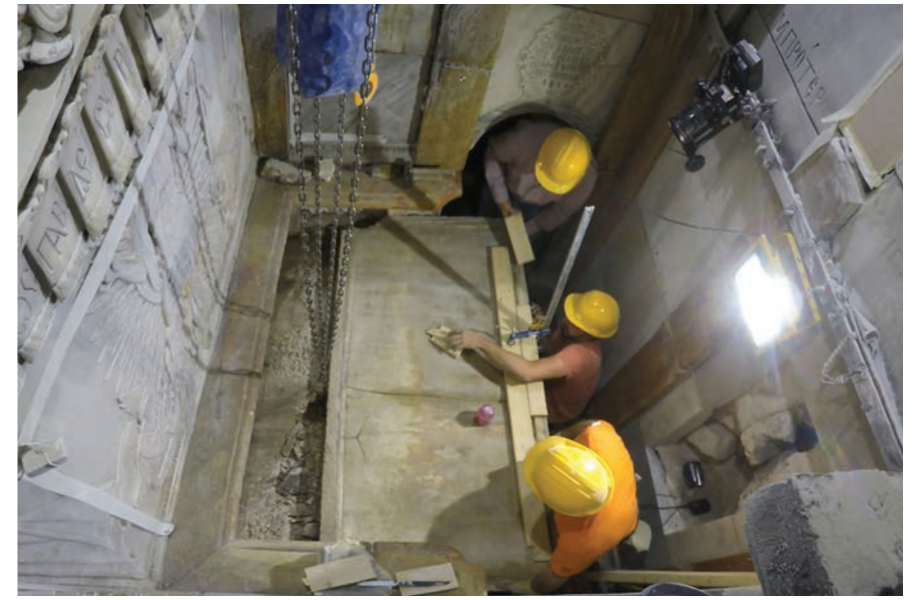
Unfortunately, some parts of the masonry—mainly corresponding to the areas around the tomb chamber—were in such a poor state of preservation that reconstruction was required to ensure the aedicule's structural integrity. The existing, low-strength masonry was removed, in some cases up to a height of 2 m and to a depth that varied depending on the curvature of the remnants of the Holy Rock. During this process, a special 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 as 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 documentation of 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 opening of the Holy Tomb involved lifting a marble plate, *above.* A glass window, *below,* was installed at the south wall of the interior of the tomb to provide views of the Holy Rock.

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The grouting was carried out in three zones along the height of the aedicule. The first zone began at the floor level and moved 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—after 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 grout material that would then solidify inside the tomb. To open the tomb involved lifting a large marble slab that was embedded 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 grout 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 grouting of the second and third zones also had to be undertaken with considerable care so as to not damage the interior frescoes.

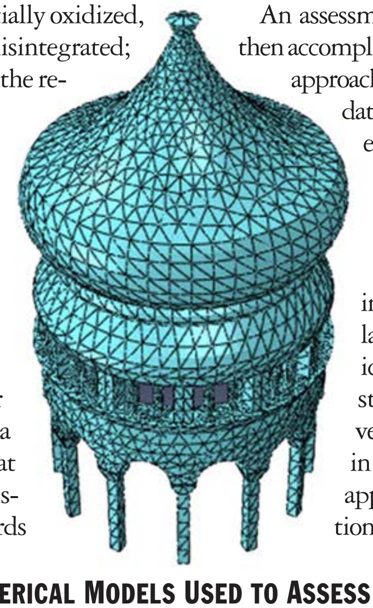
The internal marble cladding of the aedicule is part of the load-bearing structure, and thus none of its members could be removed. The Coptic Chapel, however, which is a small, partially enclosed space framed in iron lattices, was relocated from the west side of the aedicule to another section within 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; a corrosion inhibitor was applied to preserve the remaining sections of the rods.

Following the strengthening of the main masonry, the external stone panels were reassembled. The first step in this process involved the use of titanium bars to anchor the cladding. Titanium 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. So they were passed through a deformer that created closely spaced ribs that differ from those of steel rebar in terms of distance and shape. While literature and standards exist that describe the bond created between steel rebar and concrete or masonry, those documents were not applicable to these specially deformed titanium bars. Instead, a series of extensive pull-out tests were conducted on the proposed titanium anchorage techniques. 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 and a dolomitic limestone with a pink hue and touches of beige.

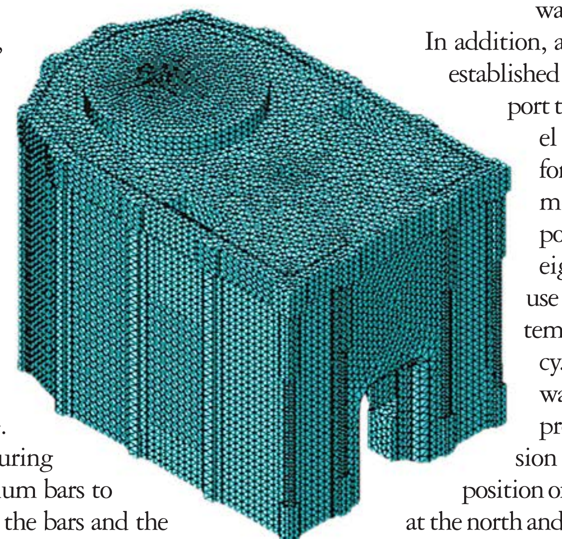
Two key details were examined during the tests: the connection of the titanium bars to the cladding, and the bond between the bars and the existing interior wall. One end of the deformed bars was either threaded or curved. Two different types of connections between the titanium bars and the stone cladding were adopted. In the first case, a hole was drilled in the stone and the threaded end of the titanium bar was fixed with a titanium nut and washer; the hole was then filled in with a matching piece of stone. In the second case, the curved end of the bar functioned as a hook. Depending on the depth of the masonry wall, the test then used either a nut and a washer—in the case of walls with shallow depths—or a deformed bar was anchored directly to the wall using mortar, in the case of walls with greater depths. A compatible and performing restoration mortar was used, presenting a compressive strength of 16 MPa over a period of 28 days and a bond strength of 0.15 MPa. The mortar was injected into a 20 mm diameter hole for the nut-and-washer test or a 38 mm diameter hole for the mortar-anchorage test.

A titanium mesh was then installed over the strengthened masonry to augment the bond between the successive concrete layers. After the reassembly of the slabs, a compatible and performing restoration concrete was added in the layers between the external stone slabs and the reinforced masonry.

An assessment of the rehabilitation interventions was then accomplished through an integrated interdisciplinary approach. Throughout the rehabilitation process, all data pertaining to the materials were documented, including the volume and distribution of the grout, the spatial quantifications of the applied concrete, and other details. A 3-D geometric model of the aedicule was created through automated 3-D imaging combining high-resolution digital images, terrestrial laser scanning, and highly accurate geodetic measurements to represent the state of the structure following the rehabilitation interventions. This 3-D geometric model was used, in conjunction with information regarding the applied materials and implemented interventions, to optimize the finite-element model. This optimized model was used to assess the retrofitted bearing structure, and it confirmed that structural integrity was indeed achieved.



Numerical Models Used to Assess the Dynamic Behavior of the Holy Aedicule



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In addition, a network of reference points was established around the Holy Aedicule to support the georeferencing of the 3-D model and to monitor the eventual deformations and displacements of the monument. A 3-D network composed of 20 points was measured in eight different phases through the use of a high-precision surveying system with a ±1 mm coordinate accuracy. A permanent monitoring system was also established and activated to provide continuous remote supervision of the structure. The changes in position of the different parts of the columns at the north and south facade of the aedicule could be determined for the last 70 years because the British engineers who installed the iron frame in 1947 also registered the deviation of each column from vertical at that time. The results from this assessment convinced the rehabilitation project members that it was safe to remove the iron frame, thus "freeing" the Holy Aedicule after 70 years.

The work revealed that the problems in the bearing structure of the monument surrounding the Holy Rock were, indeed, extremely serious. If these problems had not been addressed now, the net impact on the monument would have been negative and irreversible.

The Holy Aedicule is now at a state in which structural integrity has been ensured, deformations and displacements have been negated, and the exterior and interior surfaces have been cleaned, protected, and highlighted. But the ultimate goal of any rehabilitation project, especially one that concerns such an emblematic monument, is its sustainability. Throughout the work, the ongoing documentation and monitoring was an essential tool not only for making decisions but also for elucidating factors that could jeopardize the monument's sustainability.

A critical example involves the problems of rising damp and moisture transfer within and around the aedicule. These concerns were discovered in the initial stages of the work during the monitoring of the nondestructive testing and the use of infrared thermography. Correlation of these findings with the poor state of preservation of the filling mortar and parts of the main masonry resulted in an investigation of the surrounding underground areas using geophysical methods, including the systematic documentation of a network of existing 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.

Likewise, the geometric documentation of accessible underground 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 water-storage infrastructure within the church throughout its 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 vapor condensation, leakage, and moisture transfer. The close proximity of such areas to the aedicule underlined the need to monitor and control 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 described above. These efforts addressed the moisture-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 at the roof of the aedicule. The new system monitors 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 wall of the tomb chamber so that pilgrims could view the remnants of the Holy Rock. Data acquired from the monitoring system permits the dynamic adjustment of the function levels of ventilation and dehumidification systems. This is a critical issue, as the aedicule will have to sustain and address increasing environmental loads because of the rising number of pilgrims each year.

The second approach to controlling the transfer of moisture, which has not yet been fully implemented, focuses on the foundations of the Holy Aedicule and will involve interventions to underpin and reinforce those foundations, while also controlling water and humidity levels at the site. To this end, an integrated study is being implemented to determine exactly what type of foundation currently supports the aedicule. The study will also document the locations of conduits, cisterns, and other underground voids in the proximity of the aedicule; assess the structural condition of the foundations and their current state of reliability; and analyze the effects of long-term ground deterioration on foundation settlement and tilt.

To date, the study has determined that the surface of the natural rock of the quarry below and close to the foundation of the aedicule is strongly irregular, reaching about 3 m below the floor. Neither the aedicule nor the pillars of the Rotunda are founded directly on natural rock. Instead, they are supported on either a thin bedding layer of low silicate mortar, 20 to 30 cm thick, that has degraded because of the long-term effects of moisture, or they are founded on the rubble of older structures that are possibly not sufficiently consolidated.

A numerical analysis of the aedicule's foundation system reveals a differential settlement of the structure because of a long-term reduction in the rubble's stiffness. The proposed interventions will involve the excavation of the natural rock and the construction of a peripheral drainage and ventilation gallery, in combination with grouting of the rubble and/or removing it and replacing it with compatible and performing mortar and stonework. An excavated area south of the aedicule will be drained and ventilated, and the existing reinforced-concrete slab of the floor will be replaced by a 15 cm thick glass-fiber-reinforced concrete slab that might also feature a glass opening to facilitate an inspection of the antiquities. The peripheral drainage and ventilation gallery will include the installation of an open canal and pipes in a space below the perimeter gallery to drain the rising underground water between the new foundation and the natural rock. A ventilating system will be constructed for the best aeration and humidity regulation of the perimeter corridor, the cistern, and an earlier excavation site. In addition, a new functional sewage and rainwater network will be constructed within the perimeter of the Rotunda to replace the complex existing network.

The rehabilitation of the Holy Aedicule was successfully completed as planned and on time, with financial transparency and economy. An inauguration ceremony was held on March 22, 2017—exactly one year after the signing of the agreement that launched the restoration effort. Thanks to that effort, and a cooperative calendar, the three Christian communities each celebrated Easter on April 16 at the restored monument.

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. **CE**

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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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