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INTERDISCIPLINARY PROJECT FOR THE CATHOLICON REHABILITATION OF THE VARNAKOVA MONASTERY

Athanasia Psalti[1], Marilena Tsakoumaki[1], Georgios Andriotakis[2], Julia Vobiri[2], Charalabos Mouzakis[2], Nikos Moropoulos[2], Vasilis Keramidas[2], Maria Apostolopoulou[2], Ekaterini Delegou[2], Antonia Moropoulou[2]

[1]Ephorate of Antiquities of Phocis, Ministry of Culture and Sports, Hellenic Republic, Delphi, Greece
[2]National Technical University of Athens, NTUA interdisciplinary team, Iroon Polytechniou 9, Zografou, 15780, Athens, Greece

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Corresponding author: Antonia Moropoulou (amoropul@central.ntua.gr)

ABSTRACT

The Monastery of Varnakova is one of the most important and oldest religious complexes in Greece with high historical significance. The Catholicon was reconstructed in 1831 on the remains of the 11th century structure. Today it is in a bad state of preservation, as it has been severely affected by strong earthquakes and presents serious problems regarding both its stability and aesthetic values. Because of the importance of the monument and taking into account its poor state of preservation, a thorough diagnostic study was conducted through an interdisciplinary approach, which involved historical, architectural and structural analysis, as well as materials characterization and diagnosis of decay patterns, in order to propose an optimized rehabilitation plan. Techniques used included a 3D laser scanning and photogrammetric techniques, UAV images, a Total Station survey, 3D textured model using various techniques and software, prospection by ground penetrating radar (GPR), infrared thermography (IRT), finite element (FE) software, X-ray diffraction (XRD), Differential Thermal and Thermo-Gravimetric Analysis (DTA-TG), polarized light microscope examination, structural and mechanical properties for material restoration (e.g. stones and mortars), as well as historical stone mechanical strength tests. The history and description of the monument are presented, while the preservation state and the risks that are imposing the need for restoration, as well as the conceptual proposal of restoration, follow the pathology and decay diagnosis of the monument. Digital documentation permits the fusion of the various disciplines' data, hence allowing for the integrated design of interventions. The dynamics of the digital reconstruction allow for the adjustment of the restoration process according to the findings. Thus, the rehabilitation plan, which has initiated, takes into account and combines the findings of all scientific fields and proposes the use of new compatible and performing restoration materials and appropriate rehabilitation actions, capable of ensuring structural integrity and highlighting the values of this important monument, within an innovative project management scheme and in a dynamic manner, throughout the implementation of the project. This is an exemplary work transferring the model of the Rehabilitation of the Holy Aedicule project to Greece, based on a transdisciplinary approach and multi-actors' cooperation.

KEYWORDS: Varnakova, interdisciplinarity, historical documentation, architectural documentation, monument protection, structural analysis, restoration, materials characterization, non-destructive testing.

1. INTRODUCTION

The Virgin Mary Monastery of Varnakova is one of the oldest and most important religious complexes in Greece. The Catholicon was first constructed in 1077 AD, with subsequent construction phases (Ostrogorsky, 1969). During the Greek Revolution the Varnakova Monastery Catholicon was blown up and reconstructed by Kapodistrias in 1831 on account of its high architectural and historical significance. Strong earthquakes have resulted in important structural damages, demanding the installation of elements to contain the Catholicon and making it inaccessible to visitors. The Monastery Cells (dwellings) were destroyed in a devastating fire in 2017 and remain in a bad state of preservation, demanding almost complete reconstruction.

Monument protection is a field which demands the cooperation of scientists from different disciplines, on account of the many aspects which a restoration project must address, including historical and architectural values, structural integrity issues and materials compatibility and performance demands, among others, in Greece and elsewhere (Sandu and Sandu, 2013; Lysandrou et al., 2017; Zoe at al., 2018; Liritzis and Oikonomou, 2021; Raneri et al., 2018).

Thus, the diagnosis study of a monument is (or rather should be) an interdisciplinary issue. Digitalization of interdisciplinary data (photographs, measurements, drawings, etx) and the use of digital tools for data integration (3d models of elements and buildings through the use of laser scanners, integration of geometric, architectural, structural and materials data within finite element models) allows for the better cooperation and integration of all scientific field results (Mudge at al., 2007; Marra et al., 2021), thus resulting in an optimized rehabilitation plan (Moropoulou et al., 2018). The continuous update of all relevant information, regarding all scientific fields, during the project (Alexakis et al., 2018), allows for re-adjustments, providing the framework to optimize the rehabilitation project and achieve the optimum result.

The aim of this work is to provide a holistic framework, under which diagnostic studies, as well as rehabilitation projects, of important structures, can be conducted through a transdisciplinary, dynamic approach. In the present study, this approach is illustrated through the real use case of an important byzantine monument, the Varnakova Monastery Catholicon.

2. VARNAKOVA MONASTERY CATHOLICON: INTERDISCIPLINARY DIAGNOSTIC STUDY AND REHABILITATION PROJECT

2.1. *Methodological Approach*

In the present study an interdisciplinary diagnostic study and rehabilitation proposal methodology is presented, regarding the Catholicon of the Virgin Mary Monastery of Varnakova.

A program agreement between the Hellenic Ministry of Culture and Sports, the Region of Sterea Hellas and the National Technical University of Athens (NTUA) with Professor Moropoulou as scientific responsible, permitted the interdisciplinary documentation, diagnosis and study for the Catholicon of the Monastery of Varnakova. The goals of the rehabilitation project, which has initiated and is presented herein, are to ensure structural integrity of the historic structure along with shielding it from the earthquake risks, using compatible and performing materials and rehabilitation interventions in a way that the aesthetic, historic and architectural values of the monument will be preserved and revealed. The study and the rehabilitation project proposal were completed through the cooperation of experts in each scientific field and their research teams, including university faculty members, research associates, postgraduate students and freelance engineers.

Thus, initially the history and description of the monument are presented by the archaeologists responsible for the monument. This historical documentation plays a multilevel role, as it allows for the determination of the historical values that should be preserved and highlighted and assists in the interpretation of the other scientific fields documentation results. The architectural documentation and proposal take the historical documentation into account, while keeping in mind the main goals of the project. The vulnerability and structural assessment are studied on site with acceleration sensors and simulated and performed by finite element models. Concerning the diagnosis and the design of compatible and performing restoration materials, the materials' team implements (i) non-destructive testing on site along with materials characterization in order to conclude for decay and pathology of the Catholicon, as well as for the causes that triggered these problems, while (ii) the characterization of historic materials as well as the whole procedure for development of restoration material is presented. Their design, assessment, and optimization take place in order select materials capable to bear critical stresses, as defined by the structural analysis, and at the same time compatible with the historic building materials and structures. The preservation state and the risks that are imposing the need for restoration, as well as the conceptual proposal of restoration follows the pathology and decay diagnosis of the monument (e.g. relevant applications in: Chapkanski et al., 2021; Michalopoulou et al., 2020; Amer et al., 2020; Aydıngün et al., 2020; Al Sekhaneh et al., 2020; Da Silva et al., 2021; Gençern 2019).

The stages of the study include: (i) historical documentation and important aspects of the monument, (ii) architectural analysis, geometric documentation and important features, as well as proposals for restoration, (iii) on site non-destructive testing, pathology and materials decay, (iv) structural analysis, regarding the stability of the monument, before the rehabilitation project and for repair scenarios, (v) characterization of historical materials and diagnosis of their decay, as well as the design and selection of compatible and performing restoration materials, (vi) project management plan for the rehabilitation project.

The information deriving from each study stage is interconnected (provides information and receives information) with all other stages, while this process is dynamic, being implemented at the beginning of the study and continuing throughout the actual project, in order to assist decision making and achieve the optimum rehabilitation result. The digital documentation permits the fusion of the various disciplines' data, hence allowing for the integrated design of interventions. The dynamics of the digital reconstruction allow for the adjustment of the restoration process according to the findings.

Furthermore, it scientifically supports in real scale and real time, the integrated governance of the project under the responsibility of the Ephorate of Antiquities of Phocis, representing the Ministry of Culture and Sports. The ongoing decisions of the Restoration Directorate of Byzantine and post Byzantine monuments, as well as of the general Directorate of Conservation of the Ministry of Culture, along with the Owners' team, which is monitoring the works from the sisterhood of Varnakova Monastery, and the scientific team comprised by the NTUA interdisciplinary team, having the scientific supervision, with all engineers responsible for the implementation studies in cooperation with the contractor responsible for the construction site. The project management applies the above-mentioned priorities, accomplishing the goals of the project in time, with safety and sustainability.

2.2. *Investigation Techniques*

The historical documentation was conducted through the exhaustive review and comparative analysis of historical documents, relative literature, available photographs and drawings, as well as the archives of the Ephorate of Antiquities.

The architectural analysis and geometric documentation were conducted with the aid of 3D laser scanning (Leica Scan Station terrestrial scanner Time-of-Flight) and photogrammetric techniques (CANON SX620HS, SONY ILCE-7). In order to obtain a 3D textured model of the Catholicon, field and laser scanning survey, as well as terrestrial and UAV images of the exterior and the interior of the church were obtained. A control network of twenty (20) stations was established by using Total Station survey (Topcon 3000N), while the control points necessary for the image orientation and the Laser Scanner clouds registration were measured. The 3D textured model of the Catholicon was developed using various techniques and software (Leica Cyclone, Agisoft Metashape, Autodesk AutoCAD, REVIT) employing all the acquired data, as well as orthophotos of the exterior facades. AutoCAD was used for the architectural restoration proposal.

Non-destructive techniques used in situ included ground penetrating radar (GPR) prospection (MALA ProEx system with 1.6GHz and 2.3GHz antenna; analysis with MALA RADExplorer 1.41 software) and infrared thermography (IRT) measurements (FLIR Systems Therma Cam B200; analysis with FLIR Tools Analysis Software).

The structural analysis of the Varnakova Monastery Catholicon was implemented with the finite element software ABAQUS 6.14. The 3D-model of the Catholikon was based on the geometrical and architectural documentation of the structure, while the discretization of the model was achieved using the free-mesh technique. The complete cell was discretized with 3D continuous solid elements and the maximum FE dimensions per segment of the cell was adjusted such that at least two FEs described the thickness of the masonry, whereas the minimum FE dimension corresponded to the typical dimensions of the stones used in the masonry construction, including the joint mortars. The resultant FEM consisted of 285.998 nodes, 174.713 finite elements and 875.994 degrees of freedom. Modal characteristics of the structure, measured on site, were taken into account (Keramidas et al., in press). The seismic forces were based on the historical seismicity of the Fokida region, according to the current provisions of Eurocode 8 (Code, 2005) (see also Amer et al., 2017).

A variety of analytical techniques were employed to study the historical materials of the Varnakova Monastery Catholicon, as well as the different restoration mortars developed. The mineralogical composition of the materials was examined through X-ray diffraction (XRD; Advance D8 Diffractometer of Bruker Corporation) and qualitative and quantitative information regarding their composition was obtained through Differential Thermal and Thermo-

Gravimetric Analysis (DTA-TG) measurements (Regulus 2500 STA system manufactured by Netzsch in static atmosphere within a temperature range of 30–1000 ^oC with a heating rate 10 $^oC/min$). Total water immersion measurements were conducted to determine the porosity of the historical materials, accessible to water (Teutonico, 1988), while mercury intrusion porosimetry (MIP) was employed to study the microstructural characteristics of the restoration mortars (Pascal 400 Thermo-Electronics-Corporation). Total soluble salts measurements were conducted, in accordance to the guidelines of Normal 13/83 (CNR-ICR, 1983), in order to estimate the concentration of total soluble salts in the mortar samples; spot tests were also undertaken to acquire qualitative and semi-quantitative information regarding the type of salts present. Petrographic examination of the historical and quarry stones was achieved using a polarized light microscope (Leica DM2500P optical microscopy mounted with a Nikon camera). Compressive strength of the stones was tested in accordance to EN 1926 (CEN, 1999) on cubic specimens (5 cm edges), while compressive strength of the restoration mortars was conducted in accordance to EN 1015-11 (CEN, 2007) on cubic specimens (4 cm edges), using a Toni-Technik DKD-K-23301 with a loading rate up to 0.01 KN/s. Volumetric shrinkage of the restoration mortars was measured as the percentage variation of the specimen volume at the end of hardening in relation to its volume during casting.

3. RESULTS AND DISCUSSION

3.1. Historical Documentation of the Varnakova Monastery Catholicon – Important features

The Monastery of the Assumption of the Virgin (Panagia) Varnakova is one of the oldest monasteries in Central Greece. It is situated ~25 km northeast of Naupactos, on the border of Naupaktia and Dorida, in central Greece, on the foot of the Vardousia Mountains, at a height of c. 750 m, in a forest area of supreme natural beauty (Figure 1).

Figure 1: Monastery of the Assumption of the Virgin Monastery complex (left image) and the Catholicon (right image)

It was founded in 1077 AD., during the reign of Emperor Michael VII Doukas or Parapinakis (1071-1078) (Ostrogorsky, 1969). According to the marble inscription located inside the Catholicon (main temple, above the Gate of the inner narthex), the original ktetor (owner) was the monk Arsenios from Karya of Phocis. According to Orlandos, it was a domed basilica and consisted of three parts, the main church, the inner narthex and the outer narthex. In the period of 1084-1111, the construction of the monastic complex was completed and the Catholicon was decorated with murals. In 1148 the second, more elaborate church was constructed by the emperor Manuel I Komnenos. The monastery was given with chrysovoula (official documents carrying the emperor's 'golden Seal') additional estates in terms of metochia, a fact that contributed to its development during the 12th century AD. Alexios I Komnenos (1081-1118) became a monk and was buried in the church, as also Emmanuel Porphyrogenitus, and their tombs were discovered by A. Orlandos in 1919. An inscription in a stone larnax in the monastery mentions the names "Sevastocrator Anna and Constantine" (Saitas, 1978), also from the Comnene family, since the title Sevastocrator (respected and emperor/Augustus) was created as the highest title of the Byzantine Empire during the reign of Alexios I Komnenos (Ricardi, 2015). In 1151 the construction and illustration of the inner narthex was completed, while in 1229-1230 the external narthex was built and illustrated.

After the Fall of Constantinople in 1204, the monastery came under the supervision of the Despotate of Epirus. During the Turkish occupation it constituted an intellectual center and served as Greek school in the area, while during the War of Independence in 1821 it became a stronghold of the revolution as the fighting post of oplarchegos (a chieftain) Andritsos Safakas.

In 1826 it was besieged and blown up by the military forces of Kioutachis, and was later rebuilt during

I. Kapodistrias in 1831 (Philippopoulos, 2004) with a grant of 1800 phoenix (currency which replaced the Ottoman kuruş in a rate of 6 to 1 respectively). The amount of money granted to the monastery taking into consideration the financial state of Greece at the time was considered immense and bespeaks of the importance and historical value of the monastery, which later received the characterization of 'Hagia Lavra of Roumeli' due to its turbulent life and its intellectual radiance. The reconstruction of the Kapodistrian period commenced in 1831, according to the plans of the army lieutenant and architect Andreas Gasparis Kalandros and were executed and completed by stonemasons from Epirus in 1838 (Kardamitsi-Adami, 2011). The restoration included a double bell tower according to the architectural tradition of the Ionian islands. The first and second World Wars had a disastrous impact on the monastery due to the looting that took place and while it was inhabited by the monastic community, it reached a state of total neglect by 1990 due to lack of resources. Reconstruction work in the living areas took place during the last two decades by the current monastic community. A devastating fire in January 2017 destroyed the living quarters of the monastery and a considerable number of liturgical artifacts held in the monastery, while a second fire incident in 2020 saw the destruction of the temporary chapel and of the worship icon of the monastery with Theotokos (Virgin Mary) and Child.

The complex of the monastery includes the Catholicon, which belongs to the architectural type of the three-aisled basilica Basilica with a dome, a narthex, and the modern building complex of the Kellia (dormitories). The architectural type of the Basilica although it formed the first typological base for Byzantine architecture, as adopted by the Roman judicial buildings, it was later on transformed receiving a central dome and changes in the apses of the altar and was extensively revived during the period of the Comnenian dynasty (Soteriou, 1942). It is built with coarsely worked limestone characterized by Orlandos as hammered denoting the type of craftmanship and the processing of the stone (Orlandos, 1922). The Catholicon preserves the decorated Byzantine inlaid marble floor of the 11th century (Figure 2), and in the superstructure of the exonarthex a fresco of the Virgin in the type of Hodegetria is also preserved, dating from the late Byzantine period. The frescoes and the wooden Templon date during the period 1831-1838, when the temple was rebuilt. P. Kalonaros in his study of Varnakova (Kalonaros, 1957) also refers to an important collection of archives and books kept in the library of the monastery, all of which is now lost, but a part of it still testified in the State General Archives, in the work of D. Xanalatos (Xanalatos, 1939) and in sporadic references of other monks' work. The belfry was built in the southwest corner in the first decades of the 20th century by the state architect Gasparis, while the wooden tiled roof outbuilding was added to the west side of the narthex in the 1990s.

Figure 2: Elements of the decorated Catholicon floor rich in animal and geometric representations. The decorations extend almost to the entire surface of the main church floor

The Monastery of Varnakova was declared as a historical monument in 1993 with a surrounding zone of 1000 m and it is protected according to the Law No.3028/2002 «On the Protection of Antiquities and Cultural Heritage in General». Taking in consideration the precarious state of preservation of the monument and the previous damage inflicted by the previously referred to historical disasters along with the earthquake of 1995, which took its toll on the building, the Ephorate of Phocis in collaboration with the central cervices of the Ministry of Culture proceeded into taking measures for its protection. The protective exonarthex was situated and in 2016 and 2019 the first immediate preservation measures were applied in the Templon, to prevent further damage. All the electrical wiring was removed, and a study was undertaken in collaboration with the Directorate of Conservation of Ancient and Modern Monuments in 2018-2019 for the restoration of the Templon (Figure 3), which is currently taking place in the premises of the Ephorate with impressive results. It is wood – carved with details in high relief, gilded with gold leaves, which were worked by usually hammering gold coins offered by donors. The dressing and treatment of the faces of the figures, reflect the folk tradition of the period, such as in the scene of the expulsion from the Garden of Eden, where the archangel is dressed like a 19th century Greek warrior, currying a curved eastern type sword.

After the fire of 2017, all sixty-eight surviving movable architectural sculptured parts of the temple were transferred in Delphi, are currently undergoing preservation, and are studied by the scientific team of the Ephorate under the Direction of the Ephor of Antiquities of co-author A. Psalti. The aim of the archaeological project is to collect all the available evidence from the architectural decoration of the monument, date them and assess the original position, use, and form. At the same time all the existing literary evidence that have survived, archive material and land contracts and building restoration reports of the 19th and 20th century are collected to restore the historical line of events that took place during the modern era. In addition, archaeological data deriving from previous archaeological reports, from trial trenches excavations during restoration projects and, the currently occurring data from the recent excavation of the Ephorate that takes place during the present project of restoration. Thus, historical documentation continues during the rehabilitation project, providing data and guiding the optimum decision making process, which can reveal and highlight the values of the monument.

Figure 3: Image of the Catholicon wooden Templon

3.2. *Architectural Analysis and Geometric Documentation*

The newest Catholicon of the 19th century (with general dimensions 23x9,39m.), follows the typology of the three-nave basilica with a dome, with a main temple, a narthex to the west and a prominent semicircular niche to the east, and comprises a fundamental rebuilding of the older church. The perimetrical masonry is 0.80m thick, while the inner masonry that separates the main church with the narthex is 0.65m thick. The three naves, both of the narthex and of the main temple, are defined by two rows of colonnades -on both sides of the longitudinal axis- which are joined together by arches. In the main church there are a total of eight columns and two pillars of square bisection to which the wood-carved iconostasis is abutted. According to Orlandos, these pillars are parts of masonry that separated the sanctum from the halls on both sides.

The wheelbase of the columns is not constant. The four central columns are equally spaced (approximately 3.78 m), forming an ideal square and supporting the dome. From this element we conclude that the original basilica also had a dome. Unlike the outer narthex, the old internal narthex was not visible in the present church. The initial separation of the temple into an internal narthex and main part was perceived by a small difference in height of a few centimetres on the floor of the main temple.

The roof of the Temple consists of a vaulting system that is composed of domes, semi-domes and groin vaults, which rest on columns and pillars. During the repair works, the roof was opened, and its construction was revealed (Figure 4). It is a complex system of the newer phase, in which the slope of the roof is formed by stone gables, the gaps between which are bridged with wooden logs. The gaps are filled with stones and mortar. Stone slabs, wooden logs, slats and tiles were placed on top.

Figure 4: Revealed roof construction (left: orthomosaic, right: detail of construction)

The monument presents a variety of pathology. The bearing structure of the Catholicon is a seismically vulnerable body, whose seismic behavior is similar to that of the basilicas, as has been historically recorded. The church presents significant demolition, which has led to the buttress of the perimetrical masonry and the support of its roof.

The temple is made externally of isodomic stonework, which shows cracks of significant width in the areas of openings and corners, as well as loss of bonding mortar. Internally, there is a significant horizontal crack at a low level, in both the northern and southern masonry. This crack indicates a possible subsidence of the foundation soil of the temple. After exploratory sections, it was found that the foundation of the temple is very superficial.

The arches in the transverse direction of the temple show significant pathology, in contrast to the arches in the longitudinal direction, which are in good condition. The arches are connected with wooden tension rods in both directions. The vaulting system of the temple is in bad condition. In its entirety, the roof of the temple is supported by beams and columns created by grids with tubular beams, which are in contact with the masonry and carry the loads of the superstructure to the floor through wooden inserts. A protective grid has been placed at the height of the column capitals to hold the falls from the superstructure. The dome is internally supported by beams perpendicular to each other, placed horizontally, while externally it is covered with cement mortar and has a clamp at three levels. The out-of-level removal of the North and South wall causes the cracking of the entire vault in all three naves.

The arches of the temple are supported by monolithic columns and two pillars inside the sanctuary. The main failures of the pillars and columns of the temple are: (i) the marble columns of the outer narthex of circular bisection are in good condition; (ii) the columns of the central part of the temple, which have circular bisection, stony and coated, present a variety of pathology with shear, flexural and capillary cracks, while this pathology reaches in many cases up to their marble base; (iii) the columns in the sanctuary are of rectangular bisection, stony and coated and show shear and flexural cracks.

The floor of the temple shows significant deformations, cracks and loss of material. Approximately in the middle of the temple and towards the south wall, a hole has been drilled for the study of the underlying hatch. At a depth of 6m below the position of the episcopal throne, two underground spaces were explored, on the south side of which a vaulted crypt begins. These underground spaces also contributed to the subsidence of the temple.

The belfry of the temple is in good condition. Its base shows loss of binder mortar and growth of vegetation.

Aesthetic problems are also detected, not only account of the pathology; the choice of stonework outside the Catholicon, degrades the aesthetic value of its interior, the floor of which is a presumption of its high art, while a burden on the overall perception of the monument is the modern wooden shed, west of the narthex, which changes the proportions of the temple and makes it difficult to perceive its historicity.

The purpose of the rehabilitation project is to revoke the pathology of the monument, which presents extensive problems from multiple earthquakes, to highlight its historical and aesthetic values, and, finally, make it once again accessible.

Architectural documentation of course continues throughout the rehabilitation project, which is ongoing, as new elements and data are revealed. During the elaboration of the study and the onsite works, new elements were revealed, such as the Komnenian phase of the Monument, on the western wall of the temple, towards the outer narthex. Thus, the rehabilitation study is continuously updated in order to highlight these elements and to improve the perception of the monument in terms of its historicity and value.

The selected architectural intervention draws its inspiration from the historicity of similar monuments and historical ensembles. It is consistent with the static resolution of the support, as well as with the building character of the temple. The principles of preserving the structural system of the monument, the compatibility of the new elements with the old materials and the minimum possible intervention in the existing ones, remain constant values that aim not only at the protection of the old historical constructions, but also provide for its shielding against seismic excitations.

The following criteria are set, aiming to remove the pathology of the monument, but also to improve its perceptual image, at the same time taking into account the demands to protect and highlight the features which emerged as important during the archaeological documentation:

- No damage must be caused to the Byzantine era floor of the Catholicon and care must be taken for the elaboration of its maintenance study.
- The outbuilding must be removed from the west side of the Catholicon, because it causes aesthetic damage to the monument and alters its shape.
- The outer surface of the walls must remain uncoated. The stone elements (doorsteps, headers, etc.) should be carefully cleaned and left unpainted and visible.
- The possible existence of murals must be investigated, before applying the coatings on the interior surfaces of the temple.
- The metal frames and metal doors and windows should be replaced with new wooden elements, of traditional form.

In order to achieve the above, a variety of actions are proposed: (i) application of grout injection; (ii) installation of tension-compression rod system in the arches; (iii) vaulting reinforcement with stainless steel mesh placement; (iv) reinforcement of the roof gables, (v) reinforcement of the temple's foundations.

The principles used to achieve the above goals are based on the Venice Charter (ICOMOS, 1966) and the other internationally recognized treaties for the restoration of monuments, adapted to the particularities and conditions of the specific monument. The main principles of the rehabilitation project are to maintain the authenticity of the monument through the maintaining, restoring and preserving of the elements that have been unaltered, as well as to highlight those that have been destroyed, but their restoration is feasible. The use of traditional materials and building methods is preferred, with the commitment that if they are deemed inadequate, there will be a parallel use of modern methods and materials, which have been tested in other restorations. Furthermore, where it is feasible, the reversibility of the interventions is desired. New materials and original parts of the monument must be subtly differentiated; the differentiation is deemed necessary for functional and historical reasons (for example, in the case of new floors). Finally, the guaranteed continuous protection of the monument is also desired in order to achieve its sustainability.

In the following figures, the drawings of the rehabilitation plan for the Catholicon are presented (Figure 5-Figure 10).

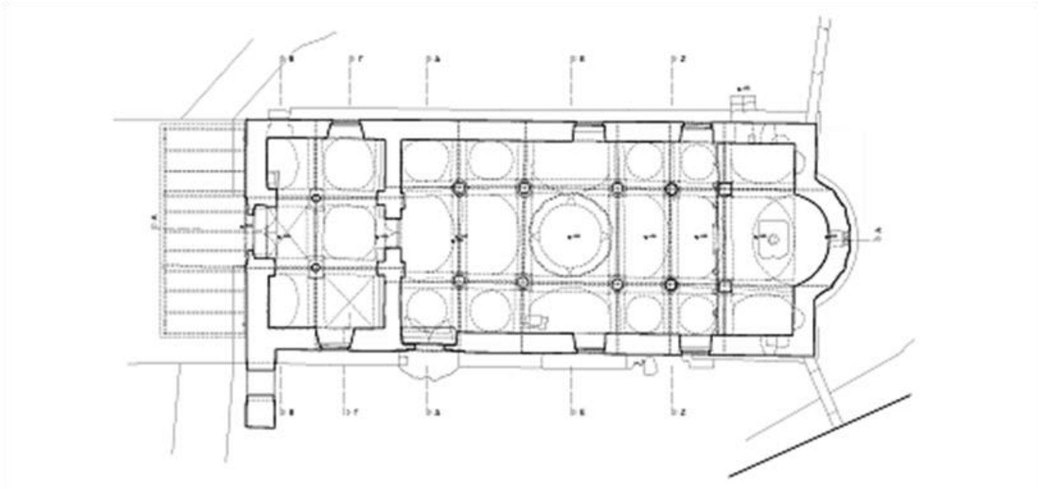


Figure 5: Plan of Varnakova Catholicon (2.5 m)

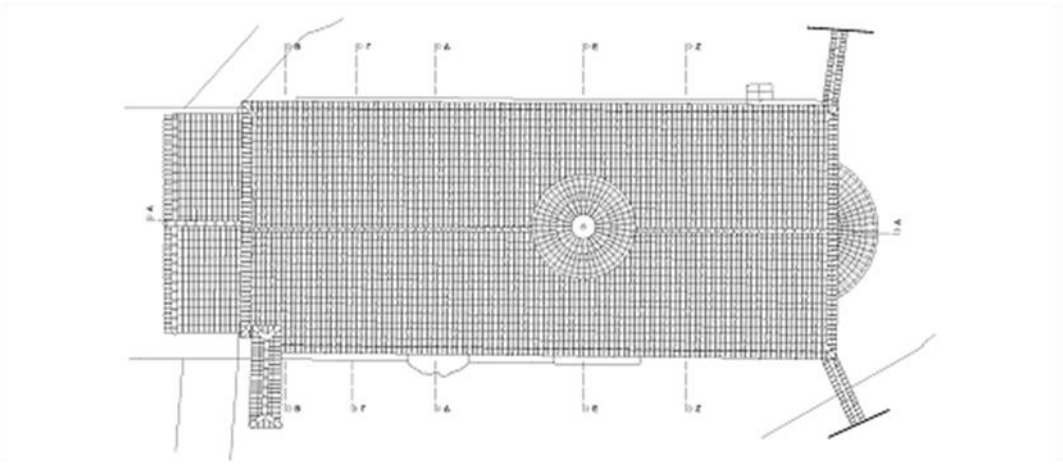


Figure 6: Roof plan

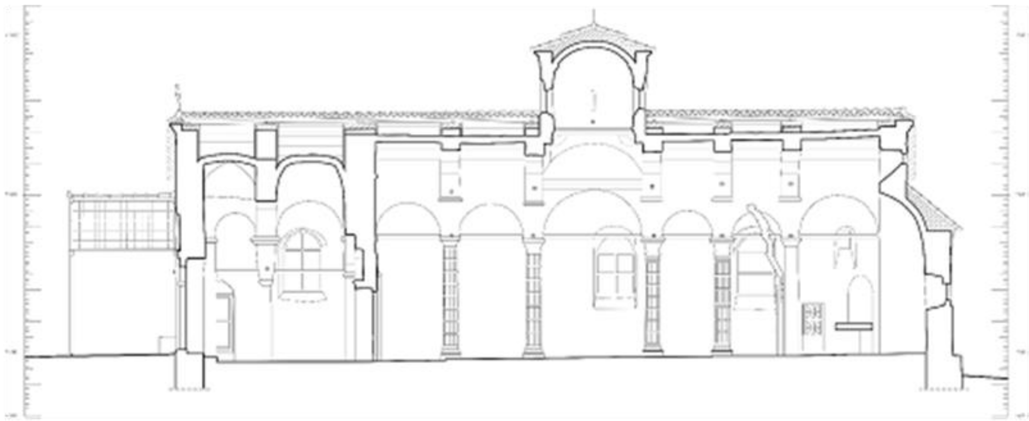


Figure 7: Section A-A - Longitudinal

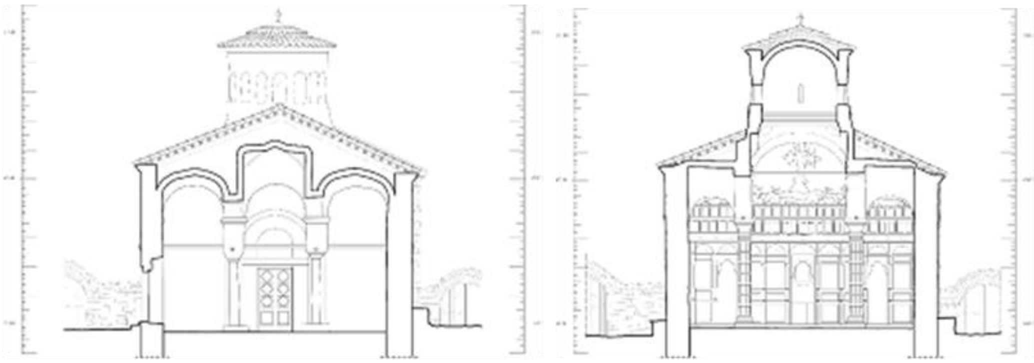


Figure 8: Section B-B - Transversal (left), section C-C – Transversal (right)

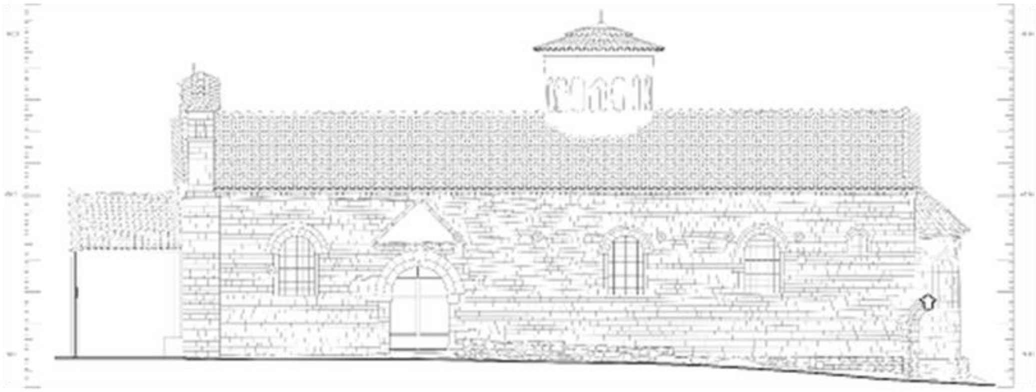


Figure 9: South view of the Catholicon

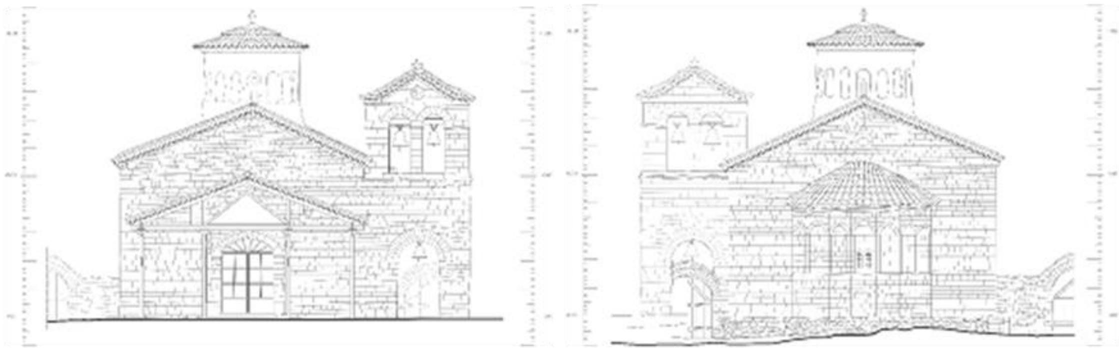


Figure 10: West view of the Catholicon (left) and East view of the Catholicon (right)

3.3. *On site non-destructive testing*

The use of NDTs during the diagnosis of a historical building or structure is extremely useful, as it can provide information regarding structural elements and non-visible configurations, the presence of incompatible materials, the presence of voids and cracks, as well as the effect of environmental factors (Bosiljkov et al., 2010; Pérez-Gracia et al., 2013; Johannesson et al., 1998; Balayssac et al., 2012; Anzani et al., 2006; Martini et al., 2017; Masciotta et al., 2007; Vidovszky, 2016; Binda et al., 2000; Moropoulou et al., 2013; Faella et al., 2012), providing information regarding both pathology and the causes of deterioration.

In the case of the Varnakova Monastery, NDT inspection during the diagnosis stage was conducted using a variety of techniques. Ground penetrating radar measurements (Keramidas et al., in press) indicated the presence of a three-leaf masonry as bearing wall of the Catholicon, consisted of two stone layers (exterior and interior, 25 cm each) and filling layer in between. Cracks which were visible macroscopically at the western segment of the north masonry of the Catholicon, were found to not extend through both stone layers and were found to not be interconnected within the internal layers of the structure. However, at the south side of the Catholicon, the reflection patterns of the ground penetrating radar (GPR) pulse around the south entrance door are interpreted to be corresponding to a detachment of the exterior layer from the filler layer. This detachment zone can potentially be correlated with the observed deformations of the Catholicon and its structural elements in this area.

Seismic sensors were applied to study the response of the monument. Infrared thermography measurements indicated areas of mortar detachment (lower temperatures) and areas where incompatible cement mortars have been used locally (higher temperatures), while it also revealed the presence of a (possibly wooden) element surrounding the structure in the internal layer (Michalaros, 2020).

The use of NDTs will be continued throughout the rehabilitation project, aiming to reveal hidden elements, provide information regarding the efficiency of the restoration and highlight new findings (Alexakis et al., 2018). The results of the NDT study were taken into account both for the selection of representative samples for the characterization of the Catholicon building materials (section 3.5), as well as in the finite element model of the structure, used for the structural analysis of the building (section 3.4).

3.4. *Structural analysis – Current state and Repair Scenarios*

In the present section the elastic dynamic numerical analyses for the investigation of rehabilitation and strengthening measures to be implemented in the Catholicon of Panagia Varnakova Monastery is investigated and presented. Time history analyses using seven real triaxial ground motion records were carried out for significance damage (SD) and near collapse (NC) limit states. The presented analyses show that strengthening measures improve the seismic response of the structure for both limit states. For the analysis, the results of the architectural study, as well as the nondestructive testing results, were taken into account.

The Catholicon structure was modeled in the Abaqus 6.19 using 3D continuous solid elements (Figure 11) (Mpletsas, 2019). Concerning the investigated interventions, the reinforced mortar jackets were modelled with shell elements, whereas the steel ties with beam elements. Finite element dimensions were selected so as at least two elements were along the thickness of the structural elements, while masonry elements had dimensions equal to the respective dimensions of the stone masonry unit plus the mortar joint thickness, considering masonry as a homogenous material. The structure was considered fixed at the foundation level.

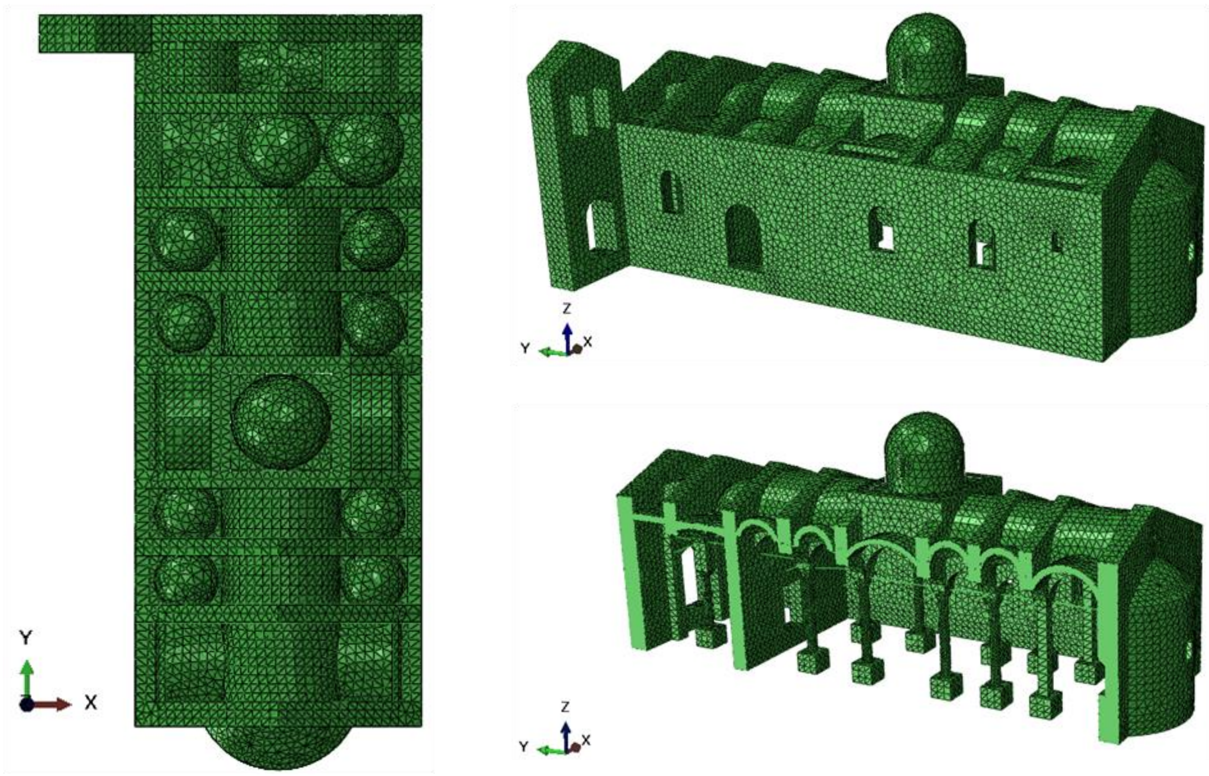


Figure 11: Meshed three-dimensional model of the Catholicon in Abaqus

Elastic material behavior was considered for the following materials: the marble of the columns, the low-strength porous stones, the reinforced mortar jackets and the steel ties. For the above process, the results of the materials characterization study were taken into account (section 3.5). The strengthened masonry was modelled inelastically using a 3D-stress constitutive law for cyclic dynamic loading, taking into account tensile, compressive and shear failures, developed using a VUMAT subroutine in Abaqus/Explicit.

Initially, modal analysis was carried out considering the strengthened state of the structure. The fundamental frequencies along X direction (1st and 2nd modes) were equal to f1=5.42hz and f2=5.66hz, while in Y direction the values were f4=9.01hz and f5=9.35hz. As expected, these values differ from those determined from microtremor measurements of the Catholicon, which were equal to 2.93 hz and 4.88hz, due to the highly damaged state of the structure. The mode shapes are presented in Figure 12.

Elastic time history analyses were carried out, implementing a triaxial ground motion (acceleration) at the base of the Catholicon model. Two limit states (LS) were considered, namely Significant Damage (SD) and Near Collapse (NC). The seismic hazard for the Monastery area was determined considering the surrounding active faults, historical seismic events records from antiquity to the present, probabilistic seismic hazard analysis and the new EC8 draft for time history selection. Considering consequence class CC3-a and soil category B, for SD limit state the peak ground acceleration (pga) is equal to 0.35g, while for NC limit state pga=0.34g. For each limit state, a suite of 7 triaxial earthquakes was selected after spectral compatibility checks with the relevant EC8 spectra, taking into account the fundamental periods of the structure in the two horizontal directions (NTUA Interdisciplinary team, 2020a; 2020b; Code, 2005). The used time histories applied are presented in Table 1.

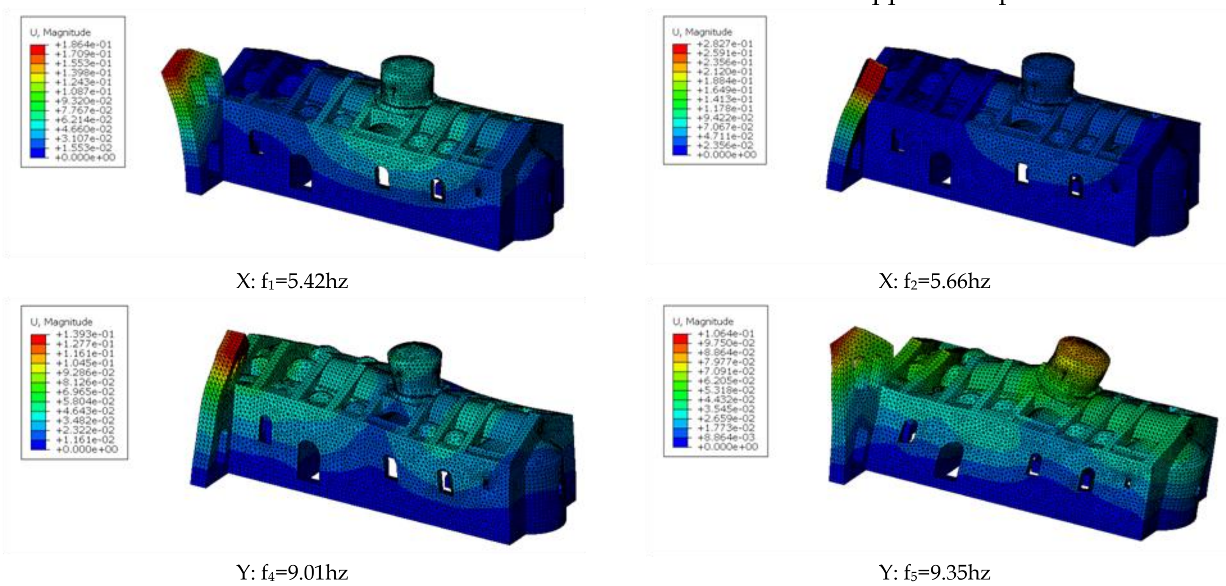
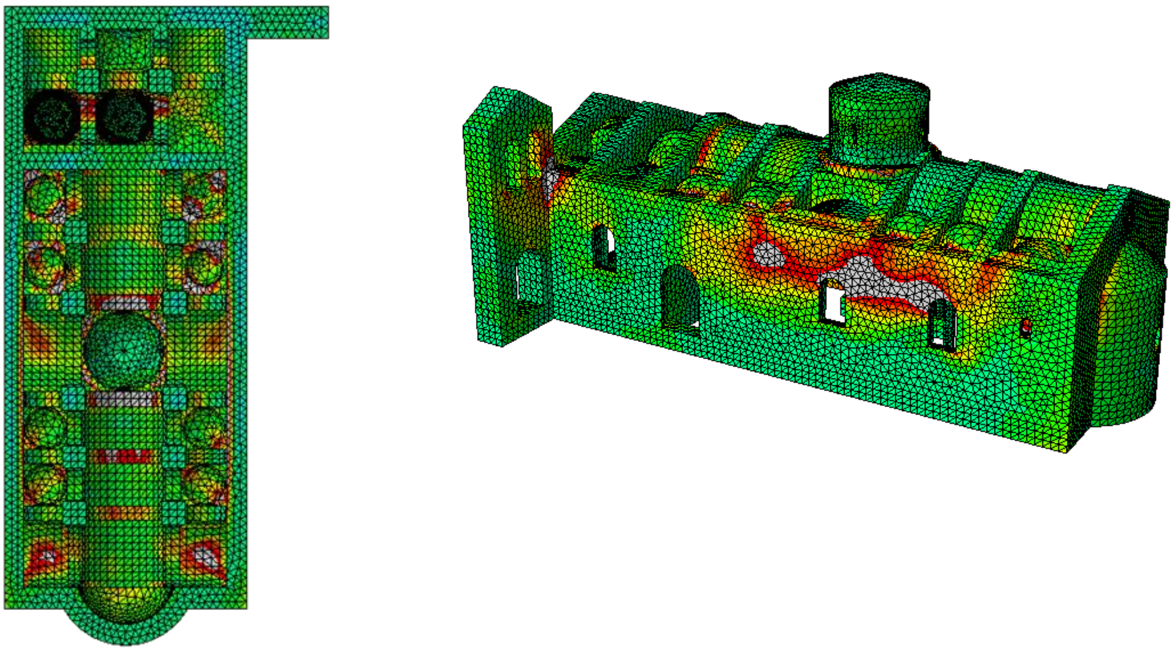


Figure 12: Fundamental frequencies and mode shapes

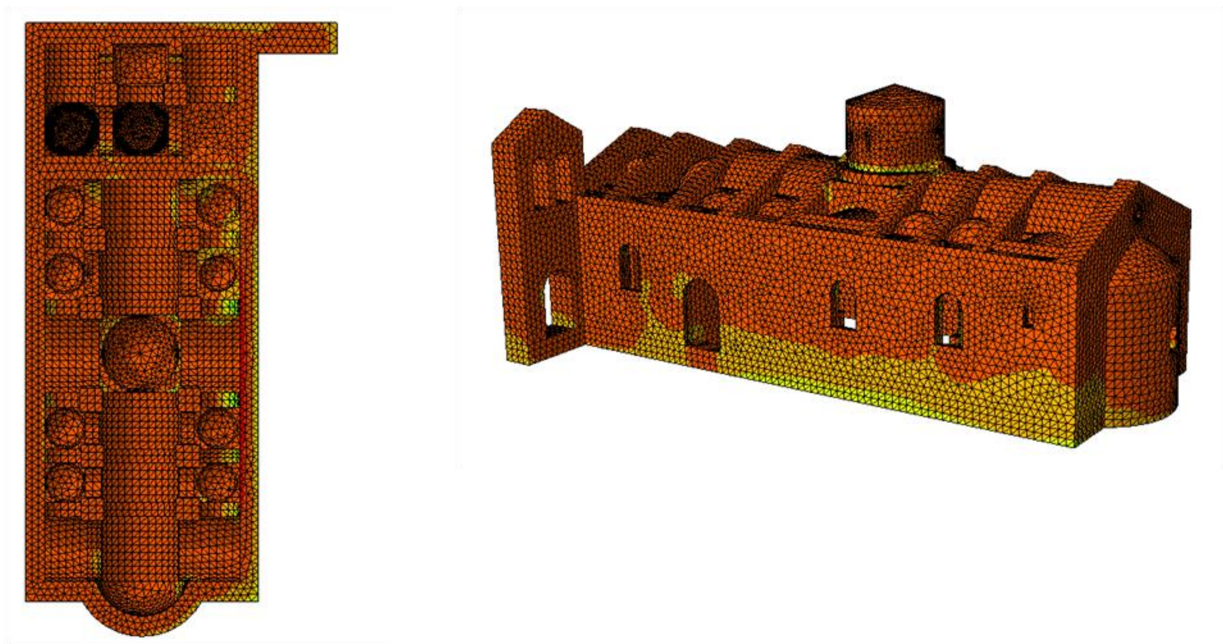
Table 1: Selected time histories for dynamic analysis

#	Database number	Seismic Event	Year	Station	M_w	Scaling Factor
SD limit state						
1	IT.AQK	L_Aquila	2009	L'Aquila-V. Aterno-Aquil Parking	6.1	1.15
2	IT.TLM1	Friuli_1st_Shock	1976	Tolmezzo Centrale-Diga Ambiesta 1	6.4	1.12
3	IV.T1244	Central_Italy	2016	Spelonga	6.5	1.50
4	RSN 763	Loma Prieta	1989	Gilroy – Gavilan Coll.	6.93	–
5	RSN 1510	Chi-Chi, Taiwan	1999	TCU075	7.62	1.25
6	RSN 3473	Chi-Chi, Taiwan-06	1999	TCU078	6.3	–
7	RSN 4213	Niigata, Japan	2004	NIG023	6.63	1.25
NC limit state						
1	3A.MZ102	Central_Italy	2016	Accumoli Madonna delle Coste-ENEA	6.5	–
2	IV.T1299	Central_Italy	2016	Amatrice, Casale Bucci	6.5	1.20
3	RSN 139	Tabas, Iran	1978	Dayhook	7.35	1.10
4	RSN 150	Coyote Lake	1979	Gilroy Array #6	5.74	1.15
5	RSN 802	Loma Prieta	1989	Saratoga – Aloha Ave	6.93	1.20
6	RSN 982	Northridge-01	1994	Jensen Filter Plant Admin. Building	6.69	1.10
7	RSN 1013	Northridge-01	1994	LA Dam	6.69	1.35

Rayleigh damping equivalent with ζ=6% was considered in all analyses. Regarding failure criteria, for SD limit state failure was determined when principal tensile stresses from G+E/q combination exceeded the tensile strength of the grouted masonry (f_t=0.30MPa). According to EC8, the final seismic response of the structure is the mean value of the response to the 7-time histories of the suite: for each ground motion, the envelope of the maximum and minimum principal stresses is calculated (these values are not simultaneous); then the mean of the seven round motions is determined and the stresses due to vertical loads is added. Considering behavior factor q=1.5, extensive masonry damage was observed. Indicative results are shown in Figure 13.



Principle tensile stresses



Principle compressive stresses

Figure 13: SD limit state – mean values of principle stresses envelope

For NC limit state (maximum considered earthquake), the failure criterion is the limitation of the inter-story drift at various critical locations, such as the drum of the main dome and the apse of the sanctuary, from the G+E combination to 1‰. Figure 14 presents some indicative drift time histories; in the end, the drifts at the examined locations were just below the critical value to avoid collapse. The suggested interventions, taking into account the structural analysis of the building, as well as the proposed architectural proposals, are the following:

- Global grouting of all Catholicon masonry and domes.
- Installation of steel struts-ties in the arches.
- Instead of placing stones over the timber structures, the roof will be reconstructed using marine-grade plywood of 22mm thickness, onto which byzantine tiles will be screwed.
- The plywood will be placed over timber beams of 8x16 cross-section.
- The timber elements will be supported by reconstructed pediments over the arches; a compatible M15 restoration mortar will be used as mortar.
- Struts-ties will be installed at the base of the arches along both directions in the interior of the temple. The struts shall consist of rectangular stainless steel (AISI 304) hollow section 100x100x10, while the struts of circular stainless steel (AISI 304) bar of 30mm diameter.
- The interior and exterior of the domes will be lined with stainless steel meshes in the restoration mortar of 50mm thickness, as well as the interior of the sanctuary apse.
- Installation of in-plane steel tie in the sanctuary apse.
- Stainless steel hoops of 50mm thickness/500mm along the height of the columns, taking into account the crack patterns of the columns.
- Concrete tie beam at column foundations.

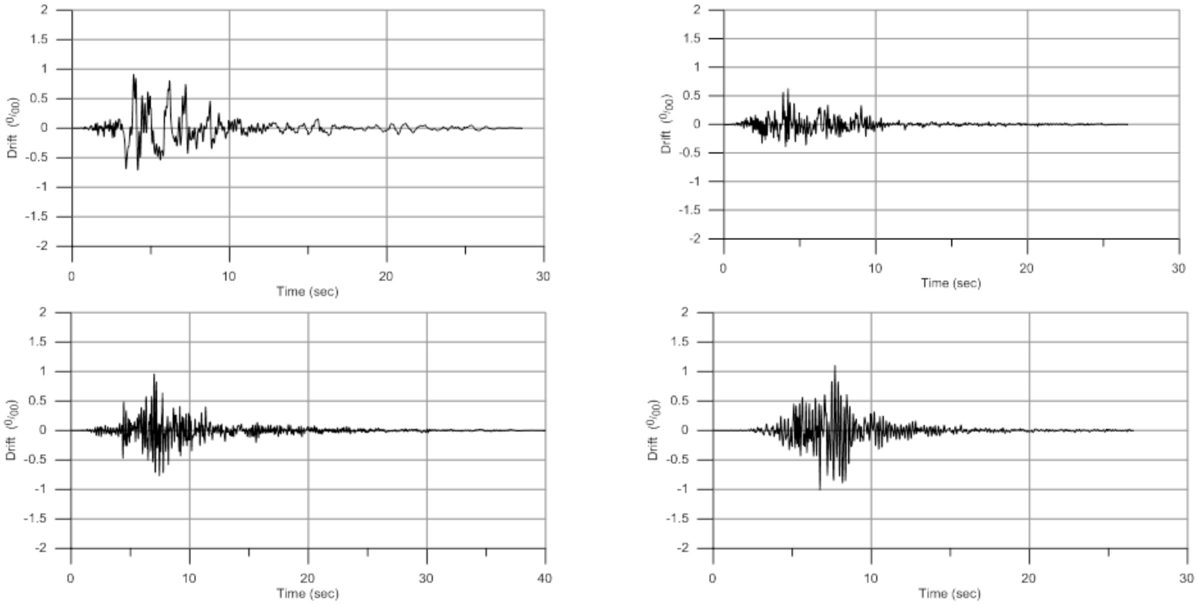


Figure 14: NC limit state – indicative drift time histories at critical locations

The presented analyses show that the rehabilitation of the Catholicon with grouting of the masonry and steel ties has the following effects, when considering pga=0.24g and behavior factor q=1.5:

- The out-of-plane displacements of the north and south walls of the Catholicon are decreased. Specifically for NC limit state, the out-of-plane drift of the walls is small, within allowable limits.
- The in-plane displacements of the north and south walls are also decreased. For NC limit state, the in-plane drift of the walls is within allowable limits.
- The principal tensile and compressive stresses of the existing masonry are confined within feasible limits after global implementation of grouting, deep rejointing up to 6cm of all joints, and selective replacement of stones at crack locations, leading to limited cracks in the masonry.
- The steel ties connecting the north and south wall will prevent their out-of-plane divergence, in case of cracks.

Therefore, the suggested interventions are adequate for the enhancement of the seismic response of the Catholicon of Varnakova Monastery for seismic events of pga=0.24g with repairable damages. In case of a strong earthquake in the area, significant damage will appear in the masonry and domes, but the analysis shows that drifts are within allowable limits, so masonry collapse will be avoided.

3.5. Characterization of historical materials – Proposal of new compatible and performing restoration materials

Aiming to document the historic materials of the Catholicon and design and select compatible and performing restoration materials for the Varnakova Catholicon rehabilitation project, a methodological approach was followed. The main stages of this approach include: (i) characterization of building materials and diagnosis of decay, (ii) development of compatibility and performance criteria which the restoration materials must abide to and, (iii) design, assessment and selection of restoration materials. Through this approach, the data deriving from the diagnosis stage is utilized as input for the development of compatibility and performance criteria, as well as the determination of acceptable ranges for the restoration material characteristics, thus, in turn, guiding the design, assessment and selection of the restoration materials. Thus, this approach initiates with the study of the historical materials, as also proposed by other researchers (Stefanidou and Pavlidou, 2018; Veiga et al., 2001; Moropoulou et al., 2009; Silva et al., 2005; Groot et al., 2000; Van Balen et al., 2005; Delgado Rodrigues and Grossi, 2007; Apostolopoulou et al., 2017), integrating data relevant to the structure and the environmental factors affecting it (Apostolopoulou et al., 2017; Moropoulou et al., 2002; Apostolopoulou et al., 2018; Schueremans et al., 2011; O'Brien et al., 1995; Beck and Al-Mukhtar, 2008; Mosquera et al., 2002; Groot, 2016; Zhang, 2010).

The historical structural mortars and building stones of the Varnakova Catholicon were examined during the "Diagnostic study and assessment of the preservation of the Varnakova Monastery Catholicon through non-destructive and analytical Techniques-Proposal of compatible restoration materials" program, assigned to NTUA by the Hellenic Ministry of Culture.

The structural mortars all presented calcite as principal mineralogical component and quartz as secondary. The mortars were categorized into two basic groups; the one group was characterized as highly hydraulic, with low presence of calcareous compounds, while the second group presented a less intensely hydraulic nature and higher percentages of calcareous compounds. This differentiation is highly interlinked with the different historical construction phases of the monument, as the mortars of the first group were all selected in areas which, according to historical data (section 3.1.), correspond to an earlier construction phase (prior to 1831) (Michalaros, 2020); these results also allowed for the confirmation of the historical documentation regarding the interpretation of the available historical data and resulting construction phases. The mortars are lightweight (apparent density 1.20-1.77 g/cm3) and present high porosity values (28-53%), confirming that they are hydraulic lime-pozzolan mortars (Michalaros, 2020). Chloride was determined in all samples through spot tests, indicating that the monument is, to some extent, affected by rising damp phenomenon and precipitation effects (Delgado et al., 2016; Arizzi and Cultrone, 2011), while high values of soluble salts measured in the higher areas of the monument, where local repair works have been carried out, indicates the use and effect of incompatible repair materials, which introduce soluble salts into the masonry and increase their concentration (Arizzi and Cultrone, 2011).

Regarding the building elements of the structure, the Catholicon presented the same lithotype as building element regarding the masonries, at least in relation to the external facades which were accessible (the internal facades are to a great extent covered with plaster). This lithotype corresponds to a low porosity grey-beige fossiliferous biomicritic limestone, which was also the same building stone determined at the Monastery Cells, presented in previous research (Delegou et al., 2019; Hemeda et al., 2019). In the interior of the monument, at the higher levels, the use of lightweight porous fossiliferous stones was determined in certain areas.

Taking into account the results of the diagnosis stage (as well as NDT results, section 3.3.), as well as the finite element model of the structure in its current state and for different repair scenarios (section 3.4.), a number of criteria arose, which were taken into account during the design and selection of the restoration mortar, in order for it to be compatible and performing (Figure 15). It should be noted that researchers have indicated that lime-pozzolan mortars seem to present the appropriate microstructural characteristics, rendering them resilient in corrosive environments (Theologitis et al., 2021; Moropoulou and Bakolas, 1998; Maravelaki-Kalaitzaki et al., 2005; Groot, 2016); furthermore, in high humidity environments, hydraulic mortars are not only more appropriate on account off their hardening mechanism (through both carbonation and hydration) (Maravelaki-Kalaitzaki et al., 2005), but also seem to perform better and present higher durability and resilience (Groot, 2016).

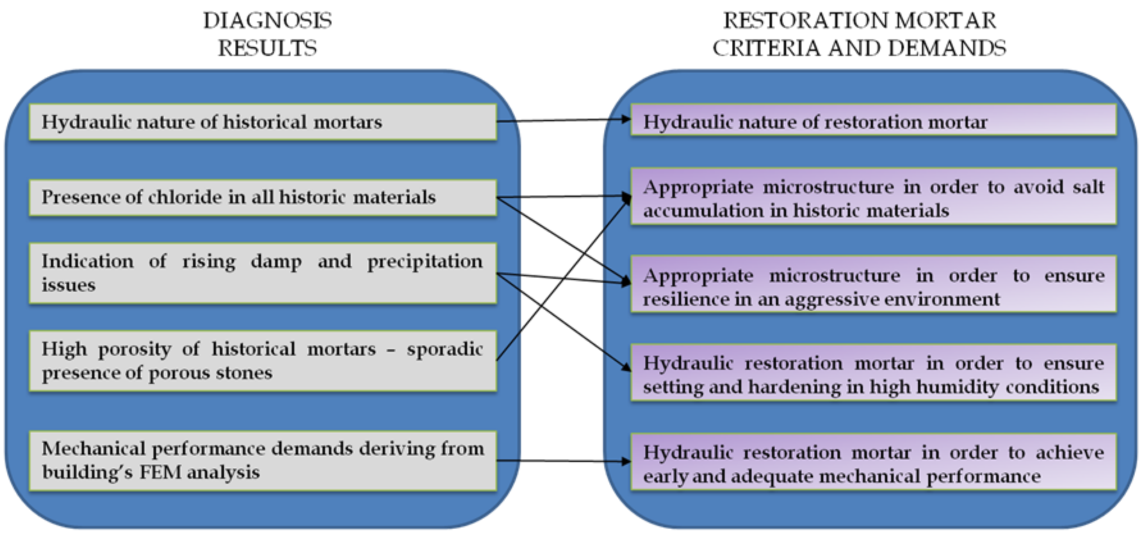


Figure 15: Diagnosis results and resulting restoration mortar criteria and demands

The compatibility and performance criteria and demands allowed for the investigation of different restoration mortars, designed through a reverse engineering approach (Moropoulou et al., 2009; Aggelakopoulou, 2006), and the selection of the most appropriate. In order to obtain adequate hydraulicity, a natural hydraulic lime was tested (NHL2), as well as different lime-pozzolan synthesis. Three different pozzolans were tested, namely brick dust, natural pozzolan and metakaolin, in different ratios (Bakolas et al., 2008, Bakolas and Aggelakopoulou, 2019; Bakolas et al., 2006). The use of siliceous sand was preferred, as siliceous aggregates seem to enhance resilience of mortars in corrosive environments (Moropoulou et al., 2009).

Table 2: Synthesis of restoration mortars

Restoration mortar	Lime Powder (%)	NHL2 (%)	Brick dust (%)	Natural pozzolan (%)	Metakaolin (%)	Siliceous sand 0-4mm (%)
NHL2_1		25				75
MK_L_1	15				15	70
MK_L_2	20				10	70
NP_L_3	7,5			22,5		70
NP_L_4	6			24		70
CP_L_3	7,5		22,5			70
CP_L_4	6		24			70

The restoration mortar characteristics were then assessed in relation to the criteria and the most appropriate mortar was selected, also taking into account the historical mortars.

The restoration mortars were assessed taking into account the demands deriving from the compatibility and performance criteria, in relation to: (i) the consumption rate of Ca(OH)2 (Figure 16), where MK_L_1 presented the fastest consumption of free lime; (ii) the hydraulicity of the restoration mortars in relation to the historical mortars after setting and hardening is complete and its relation with the historic mortars (Figure 17), where only NHL2_1 did not present adequate hydraulicity, that is its inverse hydraulicity ratio (Apostolopoulou et al., 2017; Leone et al. 2016) is lower than 7.5; (iii) their microstructural characteristics and their compliance with acceptability limits of mortars which have shown good resilience under aggressive environments (Figure 18) and specifically lime-pozzolan mortars in accordance to Moropoulou and Bakolas (Moropoulou and Bakolas, 1998), where the lime-metakaolin and natural hydraulic lime mortars in the case under examination, show the best compliance; (iv) their mechanical strength acquisition during setting and hardening (Figure 19), where the lime-metakaolin mortars show the highest and earliest acquisition of mechanical strength; and (v) the volumetric shrinkage the restoration mortars present, which must be as low as possible in order to avoid microcrack formation during the application of the material (Aly and Pavia, 2015; Pozo-Antonio, 2015), where the lime-metakaolin mortars present the lowest values (Figure 20).

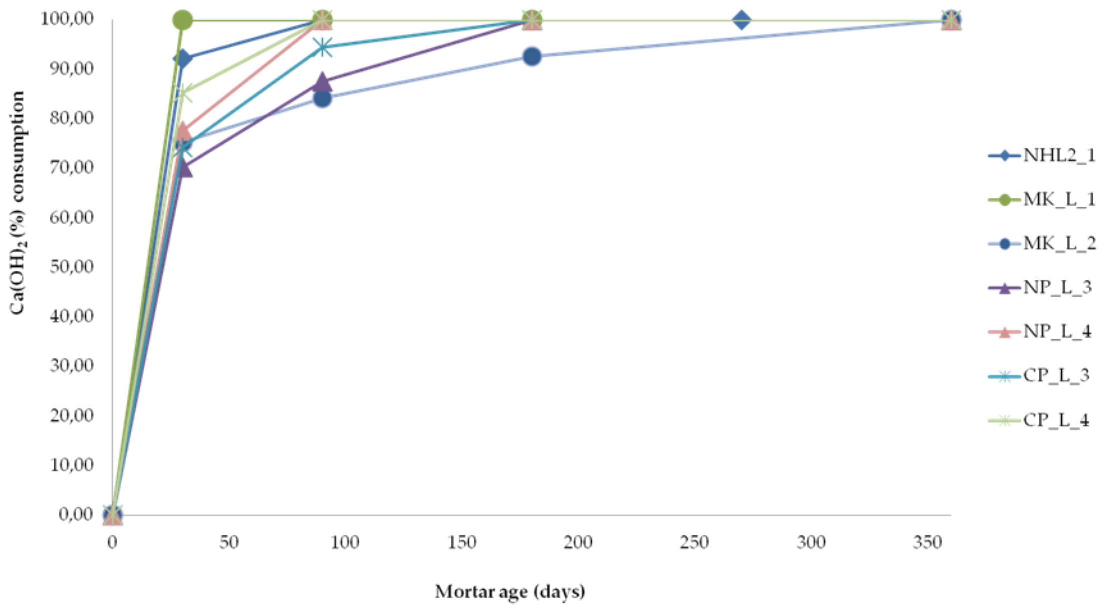


Figure 16: Consumption (%) of available $Ca(OH)_2$ in relation to mortar age

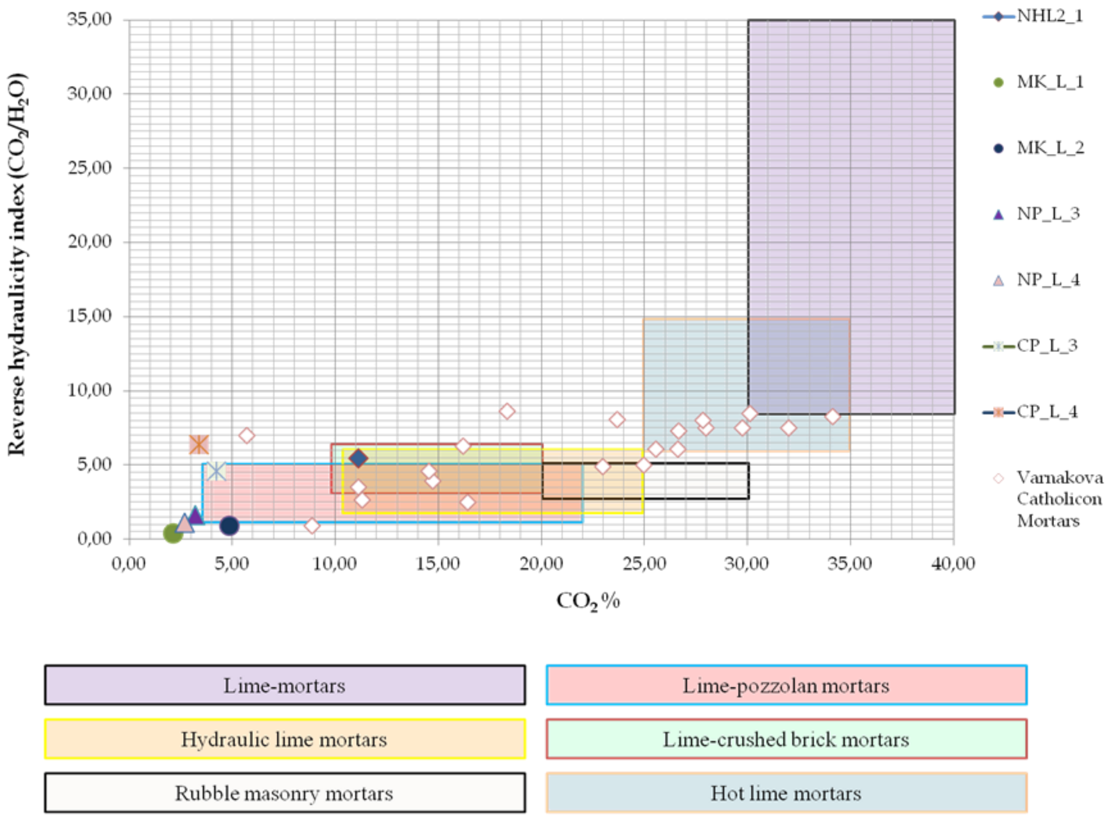


Figure 17: Thermal analysis results and correlation of CO_2 (%) loss with Reverse hydraulicity ration of restoration mortars with acceptability limits and the historic mortars of the Varnakova Catholicon Monastery

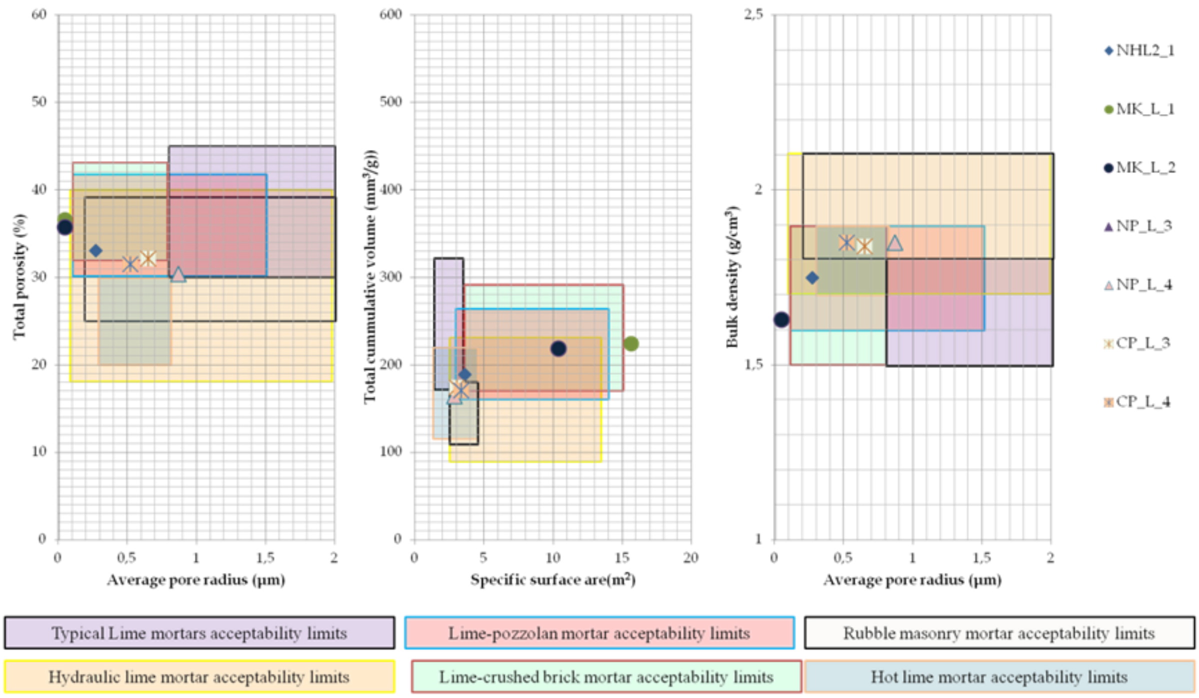


Figure 18: Mercury intrusion porosimetry results and correlation of microstructural characteristics of restoration mortars with acceptability limits

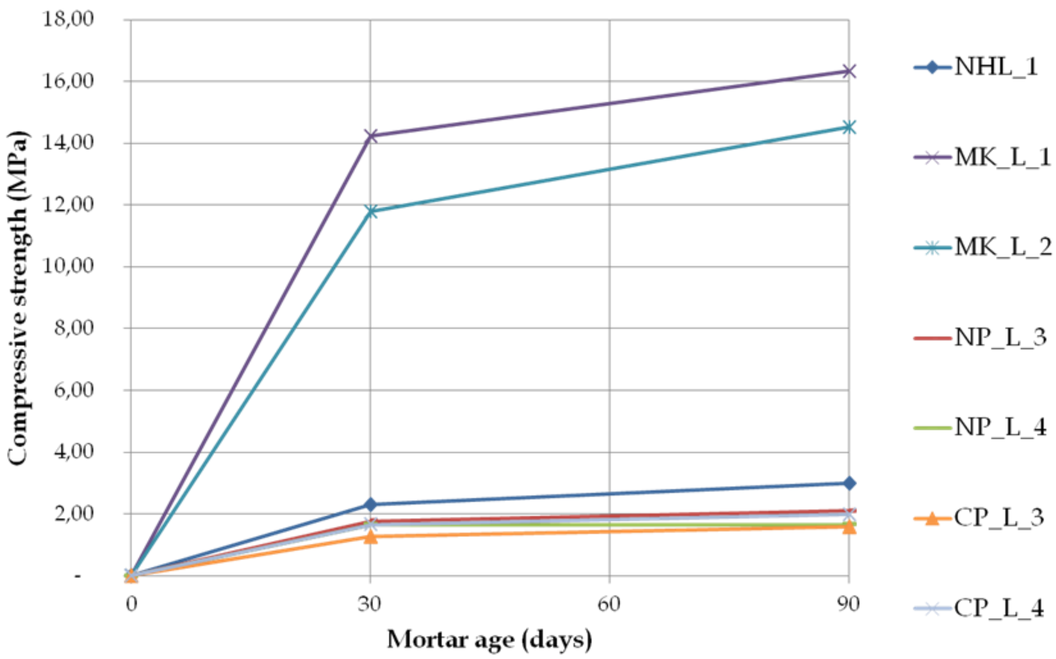


Figure 19: Compressive strength of restoration mortars in relation to mortar age

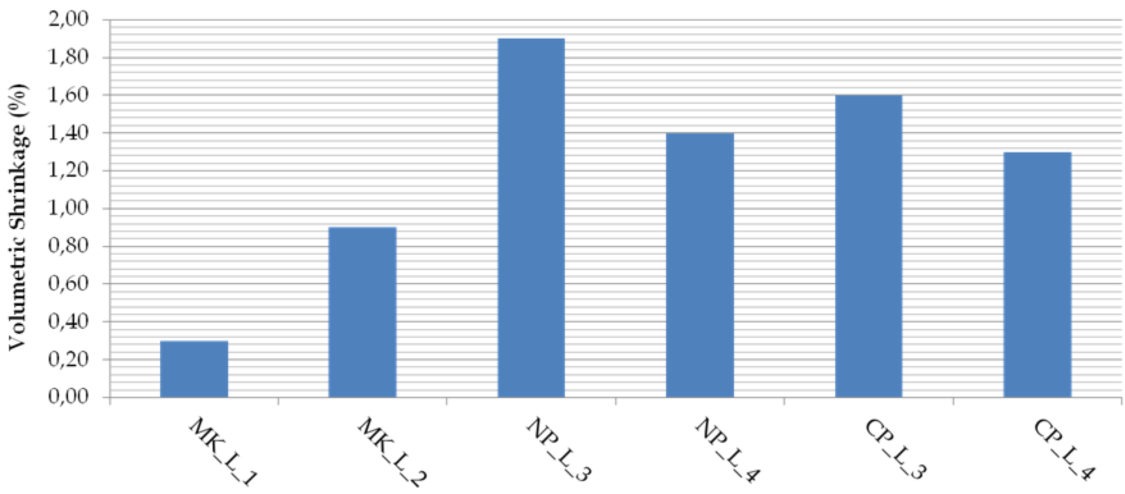


Figure 20: Volumetric shrinkage (%) of restoration mortars at the end of setting and hardening

The above analysis indicates that lime-metakaolin mortars present the highest degree of compatibility and performance for the restoration of the Varnakova Catholicon and more specifically synthesis MK_L_1. Thus, a commercial lime-metakaolin mortar is proposed for the project, which also achieves the desired compressive strength value of 15 MPa, ensuring structural stability of the rehabilitated monument in accordance to the structural stability analysis results. In addition to the restoration mortar, it was also proposed to conduct grouting of the structure, with a commercial lime-metakaolin based grout (in order to ensure compatibility) aiming to homogenize the different structural layers of the monument. Both commercial products are free of cement and within standards.

The selection of the appropriate restoration stone was conducted through a three-stage approach: (i) characterization of the main historical building stone and determination of characteristics (mineralogical, physicochemical, mechanical and aesthetical), (ii) investigation of local quarries for the same or a similar lithotype, (iii) characterization of new quarry stones and determination of characteristics (mineralogical, physicochemical, mechanical and aesthetical), (iv) comparison of all quarry stone characteristics with historical building stone characteristics and selection of quarry stone with the highest similarity (Apostolopoulou et al., 2019). This procedure was successful in the case of the Varnakova Monastery, as, among the local quarries, a quarry stone was found, corresponding to the same lithotype as the original stone and with similar characteristics (Michalaros, 2020). The new stone presented similar mineralogical, petrographic, aesthetical, and physicochemical characteristics with the original stone and slightly lower, however adequate in terms of structural integrity, mechanical properties (154 MPa compressive strength in relation to 166 MPa; 3.07 MPa tensile strength in relation to 3.53 MPa; 17.04 MPa flexural strength in relation to 22.29 MPa of the historical stone). The slightly lower mechanical properties of the restoration stone guarantee a compatible behavior and the protection of the historical building stones under static and dynamic loads. The slight differences of the stones are interlinked with the extraction of the material from different areas of the quarry today in relation to centuries ago.

3.6. Implementation of the Catholicon rehabilitation and project management plan

The current project of restoration and rehabilitation project of Varnakova commenced in 2020, after the completion of the interdisciplinary study of the National Technical University of Athens under the Direction of Prof. A. Moropoulou and approved by the Central Archaeological Council. The project forms a collaboration of the Monastery of Varnakova, the Ministry of Culture, and the National Technical University of Athens. The onsite collaboration of the participating bodies demands the cooperation of a variety of scientific specializations such as architects, civil engineers, chemical engineers, archaeologists, conservators and importantly enough the presence of a coordinated ground specialized workforce. In each section of the project that is completed, the data is reassessed by the scientists and the course of action is rescheduled. The completion of the first phase after removing the modern era layers on the walls of the Catholicon unveiled unknown parts of the first phases of the monument in the roof and the narthex, including large part of the initial masonry and walls, frescoes, and a section of the 'hidden tile' technique of the roof. As the project proceeds and the temple practically transforms to a more complex in terms of building phases monument, each course of action is reassessed according to the archaeological finds, as the primary target is the rehabilitation of the temple and to protect, preserve, respect, and portray all the historical phases of the Catholicon. Thus, archaeological, and technical documentation is of utmost importance, in coping successfully with the challenge of the concept of the restoration and its realization.

The first phase of the project included: a) the uncovering of the modern tiling of the roof b) the assessment of the stability of the building and more importantly of the central dome and the supporting arches, c) the removing of the modern era plastering from the walls d) the detection and documentation of earlier phases of frescoes, mainly in the outer narthex, where the Byzantine phase was already present and e) excavation beneath the floor of the outer narthex in order to detect previous floor levels west of the marble floor of the main temple. These preliminary actions were considered imperative by the scientific team in order to finalize the static study and propose the appropriate measures, document the archaeological phases and reassess the data to determine the building phases, the renovation interventions and the internal decoration program along with the iconographical phases.

The synthesis of the above will produce the final architectural proposal for the consolidation of the temple, which will take into consideration all of the historical phases of the monument. This forms a challenging task, because the new evidence occurring as the project proceeds, demand the use of interdisciplinary methods, in the sense of the synthesis of the approach. Yet, due to the added prerequisite of multidisciplinary knowledge, needed for the collaboration of the team, the overall scheme would be characterized as transdisciplinary, as the concept dominating the ideology of the project is to form a new innovative and inclusive unity of different disciplines collaborating not only united under a common cause, but with a common ideological concept.

The management of the project is based on the following objectives and practices:

- Communication. The continuous and open communication between all the involved parties is essential for the success of the project and is supported and practiced daily.
- Transparency. Project information is widely available to all concerned.
- Timeline. The project completion milestone is the end of July 2022. The project schedule and its management aim to meet this deadline without missing any intermediate milestones.
- Effectiveness. All project tasks are defined in such a way that the supervising engineers can check their successful completion. In this way the team that executes the tasks is enabled to perform their job effectively.
- Collaboration. The project is the result of joint efforts of a team of scientists and a construction team. These roles are not disjoint, they are supplementing one another.
- Ownership and Accountability. Each task has an owner, be it a scientist who designs, an engineer who supervises, a contractor who builds. Each owner is also accountable for the tasks they own. And they need to get them right the first time. There is no time for errors and recoveries from errors.
- Agility. Planning and scheduling for this type of projects requires agility. Work is planned and scheduled for short periods of time, using all the available information. In each iteration new information is integrated into the process and the next period is planned and scheduled.
- Reporting and Control. Bringing new data to light and reporting them is essential. Controlling the project activities by comparing the planned to the actual is a key responsibility of PM, and it includes the financial part of the project.

The project work breakdown structure provides for two stages. The first stage of the project, comprises the removal of the stones from the roof of the structure and the cleaning of the masonry joints both in the inside and the outside of the load bearing walls. At this point, this stage has been completed. Grout injection tubes have been inserted in the walls and the roof support elements. Based on the findings following the removal of the stones from the roof of the structure, the earthquake resistant design was modified and resubmitted to the Ministry of Culture for approval, which is currently pending. Following the approval, the project schedule will be revised accordingly, in order to proceed to the second stage of the project.

During the second stage grout shall be injected in the walls and other load bearing elements of the structure, all the additional elements required by the earthquake resistant design will be constructed, and the existing columns and the foundation elements will be strengthened.

Digital 3D geometric documentation by 3D scanner and its architectural integration into the relevant documentation permits the fusion of the various disciplines' data, hence allowing for the integrated design of interventions. The dynamics of the digital reconstruction allow for the adjustment of the restoration process according to the findings. The dynamics of digital reconstruction allow for the adjustment of the restoration process according to the findings. Thus, the integrated governance of the project under the responsibility of the Ephorate of Antiquities of Phocis, representing the Ministry of Culture, is scientifically supported in real scale and real time. The ongoing decisions of the Restoration Directorate of Byzantine and post Byzantine monuments, as well as of the general Directorate of Conservation of the Ministry of Culture and Sports, along with the Owners' team, which is monitoring the works from the sisterhood of Varnakova Monastery and the scientific team comprised by the NTUA interdisciplinary team having the scientific supervision with all engineers responsible for the implementation studies in cooperation with the contractor responsible for the construction site. The project management follows the above-mentioned priorities, accomplishing the goals of the project in time, with safety and sustainability.

4. CONCLUSIONS

The present study presents the interdisciplinary study and rehabilitation project proposals and rehabilitation regarding the Catholicon of the Varnakova Monastery, one of the oldest and most important monasteries in Greece.

The goals of the project are to ensure structural integrity of the historic structure along with shielding it from the earthquake risks with compatible and performing materials and rehabilitation interventions in a way that the aesthetic, historic and architectural values of the monument will be preserved and revealed.

The interdisciplinarity of the study, as well as the diversity of the research and rehabilitation team, allows for a multileveled analysis, not only in the stage of diagnosis and proposals, but also throughout the implementation of the rehabilitation project. The transfer and fusion of information from one scientific team to another, amongst scientists of different expertise, and amongst all parties involved and responsible for the monument, allows for the design of the optimum rehabilitation scenario, while the innovative project management plan allows for optimization of the rehabilitation, through a dynamic process throughout the project, according to the new findings.

This is an exemplary work transferring the model of the Rehabilitation of the Holy Aedicule project to Greece, searching out a transdisciplinary approach and multi-actors' cooperation.

The methodological approach and the interrelation of all disciplines, which emerged from this study is presented in the following figure (Fig.21):

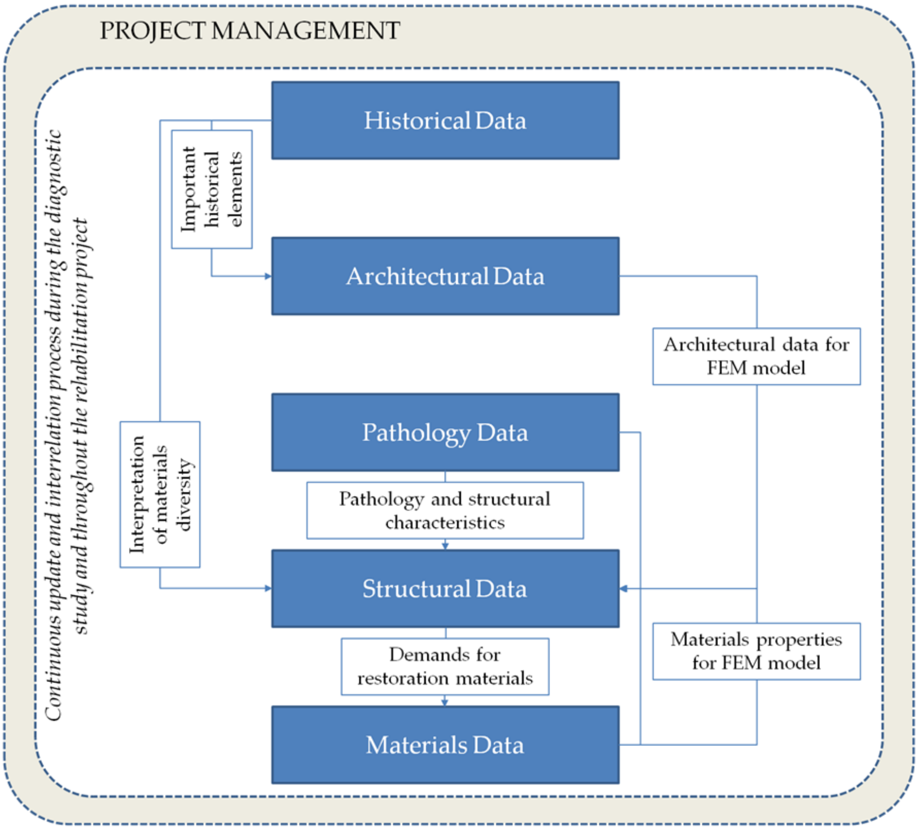


Figure 21: Transdisciplinary methodological approach for diagnosis and rehabilitation of historical structures

AUTHOR CONTRIBUTIONS

Conceptualization, A.M.; methodology, A.M., A.P., G.A., Ch.M. and N.M.; validation, A.M. and Ch.M.; formal analysis, X.X.; investigation, M.T., J.V., E.D., V.K. and M.A.; data curation, M.T., J.V., E.D. and M.A.; writing—original draft preparation, A.P., M.T., J.V., Ch.M., M.A.; writing—review and editing, A.M. and M.A.; visualization, A.M.; supervision, A.M.; project administration, A.M. and N.M.; funding acquisition, A.M. All authors have read and agreed to the published version of the manuscript.

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