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Article

Structural Behaviour and Strength Evaluation of a Venetian Church through Finite-Element Analysis

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Abstract: The evaluation of the structural behaviour of a masonry Venetian church with a pointed barrel vault is presented in this paper through an analysis following the necessary steps of a monument study. With a detailed geometric model and material estimation, the finite-element method is used to investigate the influence of specific structural parts of the structure, like masonry buttresses and wall connections, on the structural behaviour. The operational modal analysis is used to identify the structure dynamically. The comparison of the eigenfrequencies, which are estimated by in situ measurements and finite-element modal analysis, is used to perform a model identification. The response spectrum analysis, the static analysis after the subsistence of some parts following strengthening proposals, and the transient analysis of specific seismic excitations are used for the evaluation of the structural behaviour. The purpose of the work is to highlight the need for an interdisciplinary approach to the study of a monumental complex structure, regardless of its scale. The coexistence of structural elements of different stiffnesses, such as vaults, elongated walls, buttresses, transverse walls with pediment and belfry, as well as the concha, affects the mechanical behaviour and the pathology of the structure, which is difficult to study with simplifying models. From the analysis, it is concluded that subsidence problems, combined with seismic actions, lead to the cracking of the masonry, while the existence of buttresses limits the extension of the damage and contributes to the stabilization of the structure.

Keywords: finite-element analysis; dynamic analysis; earthquake analysis; unreinforced masonry; architectural survey; masonry vaults; Venetian church; single-aisle church

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1. Introduction

For the strength evaluation of a single-aisle church and of an existing building generally, a series of steps are performed. As a first step, the history of the building should be documented through the archives available in public services (e.g., archaeology, urban planning, cadaster, libraries, etc.). Then, in the case that drawings of the building are available, their correctness should be verified. Otherwise, detailed plans (plans, sections, views) should be drawn up. In the next step, in situ research must be performed on the building where any difficulty in collecting the primary data is identified. At this stage of the investigation, both the interior and exterior of the building are photographed in detail, and the existing structural damage, construction method, and construction phases of the building are recorded. In some cases, it may be necessary to remove part of the coatings in characteristic parts of the structure to make hidden parts visible. Regarding the assessment of the mechanical characteristics of the load-bearing masonry, non-destructive methods can be applied, and cores for conducting laboratory tests must be taken if possible. After the above-mentioned data have been collected, exploratory analyses are performed to identify the structural damage and its cause in the building under study. Finally, the mechanical analysis of the building is carried out based on the current regulations, with the final result being the drawing up of the static restoration study.

A vault, and especially a barrel vault, is an architectural element formed by the extrusion of a single curve (or pair of curves, in the case of a pointed barrel vault) along a given distance. The curves are typically circular, lending a semi-cylindrical appearance to the total design. The barrel vault is the simplest form of vault and is used to provide a space with a ceiling or roof. As with all arch-based constructions, there is an outward thrust generated against the walls underneath a barrel vault. There are several methods of absorbing this thrust. One is, of course, to make the walls exceedingly thick and strong. A more elegant method is to build two or more vaults parallel to each other to direct the forces of their outward thrusts to negate each other. This method was most often used in the design of churches, where several parallel vaulted naves were constructed. The traditional and modern views of vault analysis end up with the same fundamental conclusion: the overall importance of geometry on structural behaviour. An essential condition for the unreinforced material is that the internal forces must be compressive [1]. The role of some constructive aspects (brick pattern) on the shear in-plane capacity of masonry barrel vaults has been studied, and the results of the numerical simulations have highlighted that the brick pattern greatly influences the structural behaviour of vaults subjected to a horizontal settlement of the abutments in terms of ultimate capacity, ductility, and collapse mechanism [2,3]. The major simplification for modelling is to reduce the vault to a series of adjacent arches without a transversal connection. However, this model is unable to properly simulate the three-dimensional effects of the vault. The structural role of the spandrels that stabilize the vaults must be considered in the analysis of the structure [4,5].

From a review study of some methods and models that are proposed for the analysis of masonry vaults, it was concluded that all methods adopted to describe the mechanical behaviour of masonry structures, to be reliable, must take into account the distinctive aspects of masonry, namely the low (or zero) tensile strength, the good resistance in compression, and the occurrence of failure mechanisms through rotation–translation of rigid macro-blocks [6]. The advanced numerical analysis could offer significant information both for the understanding of the causes of existing damage and for the design of adequate strengthening [7]. The finite-element method and 3D models were used to study the mechanical behaviour of complex monumental structures, which consist of walls and vaults and structures with special geometry, stiffness, and mechanical behaviour, which can hardly be simulated with simplified models [8–14]. Vaults and walls are modelled by solid elements to consider details of the specific geometric and boundary conditions. For each calculation, the homogenized limit analysis approach has been employed, assuming that the constituent materials experimentally determine the mechanical properties. An accurate geometry of the vault is necessary to model the existing condition, including the permanent deformations. The modelling of the existing condition of the masonry (weak material, cracks) is important for the estimation of the structural strength and dynamic behaviour.

In single-aisle vaulted churches, the main intensive quantities causing failure are tension and shear developed due to the out-of-plane bending of walls. Of course, the special characteristics of each church affect its final strength both positively and negatively. Such characteristics can be the foundation soil, the stones that make up the masonry, the way the masonry is built (ashlar walls, rubble walls), and the connections between longitudinal and transverse walls. In addition, the shape of the vault and its support on the walls, as well as the shape of the concha and its connection to the masonry, are specific elements that influence the mechanical behaviour of this type of church.

In this study, research and analysis are presented on the main mechanisms of structural damage to a Venetian church using the finite-element method. The current scientific announcement is based on a prior study [15] that was carried out in the frame of the academic transdisciplinary courses of postgraduate degree studies in the School of Architecture at the Technical University of Crete, Greece.

Saint George Mormoris ecclesiastical glebe—metochi—is situated in the Chania valley at the northern boundary of the Nerokourou settlement. The Venetian Church of Saint George is placed at the centre of a quadrangle courtyard of a building complex. The

Venetian census [16] of the orthodox churches in Crete in 1637 refers to this church and the personnel, naming "Hemanuel Mormoris" as its owner.

The anti-seismic adequacy of Venetian churches is reduced because the existence of vaulted structures, and those with a pointed form, as was common in the Cretan architecture of the time and as a Latin architectural influence [17], does not ensure any form of diaphragmatic function for the cooperation of all the vertical elements, while the construction method with unreinforced masonry elements does not allow for the support of tensile stresses. Essentially, the horizontal components of an earthquake are assumed by the stiffness of the vertical walls—the front ones in a transverse direction and the end ones in a longitudinal direction. The seismic action imposes thrusts on the vaults on the end walls. For this reason, large dimensions are often presented in the thickness of the longitudinal walls or the construction of buttresses. The eastern wall that carries the semi-circle concha is a particularly sensitive construction from a static point of view since it is an intersection of a double curved surface with a flat support in which the deformations are not compatible everywhere. However, the existence of the semi-circle concha was essentially a support for strengthening the rear frontal wall, which explains the fact that the sanctuary is still preserved in many damaged churches.

The structural analysis of a Venetian church was carried out using the finite-element method to investigate the role of specific structural elements like the vault, the buttresses, and the concha in the structural failure development. For the modelling, the existing geometry, the history of the monument, the quality of building materials, and subsoil conditions were considered. In this paper, the operational modal analysis is based on measured eigenfrequencies. Since there exists accumulated experience with churches of similar geometric characteristics, eigenmodes are easily correlated (from the bell tower, etc.), and the damage is restricted along a measured crack. For more general cases, model identification should be based on the comparison of both eigenfrequencies and eigenmodes, possibly using some numerical optimization, namely the particle swarm optimization [18]. The response spectrum analysis for the design spectrum, according to Greek Regulations, the static analysis after subsistence of some parts, and the transient analysis of specific seismic excitations were used for the evaluation of the structural behaviour. The complexity of the monumental structure and the need to investigate many parameters and collect geometric, historical, architectural, and structural data leads to the need for an interdisciplinary approach to the structural study regardless of its scale.

2. Historical and Architectural Evidence

A branch of the Mormoris family settled on Crete in 1541 after the occupation of the Peloponnese by the Ottoman Turks. Some remarkable members of the family developed their operation as mercenaries, "Stradioti" for the Venetian army, and obtained properties and privileges in Chania [19].

The church of Saint George is categorized as a small single-aisle church with a pointed barrel vault roof located at the centre of the ecclesiastical glebe's complex, as shown in Figures 1 and 2. Occasionally, the complex is used by the citizens of the village on local feast days [20]. The external measurement of the plan is approximately 9.4 m by 6.3 m. The walls have been constructed with ashlar limestone and uncut stones. The main entrance is placed on the west facade, and a concha is directed eastwards (Figures 1 and 3).

The Venetian census [16] of the orthodox churches in Crete in 1637 refers to this church, with "Hemanuel Mormoris" as its owner.

The portal to the church is decorated above with simplified baroque-revival elements, including a scroll relief, a lintel with cymatium, and a pair of semi-pilasters on either side (Figures 3 and 4). On the top of the triangular high end, there is a double-arch belfry with metal braces. Higher on the wall, between the triangular high end and the portal, is a circular opening called the "occulus". The relief architectural features of the entrance, together with the buttresses, are assumed to be a newer construction, probably from the

19th century, where stonemasons used to reproduce earlier morphological elements of the 17th and 18th centuries [21].

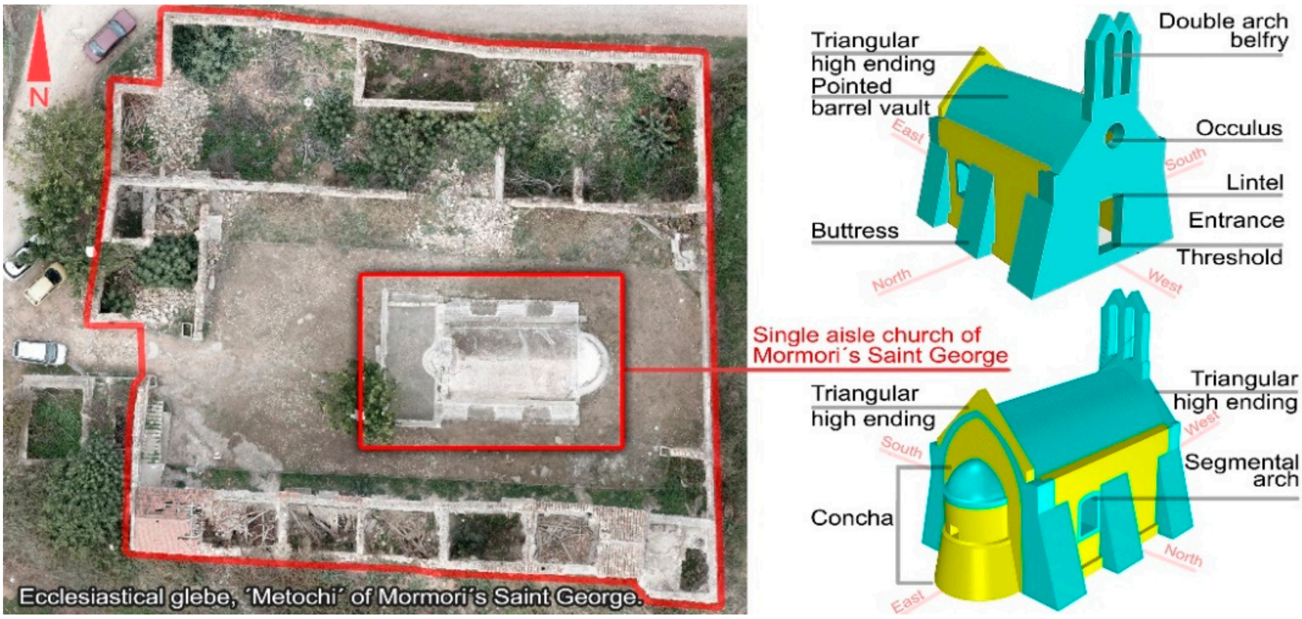

Figure 1. Plan of Saint George Mormoris ecclesiastical glebe—Metochi.

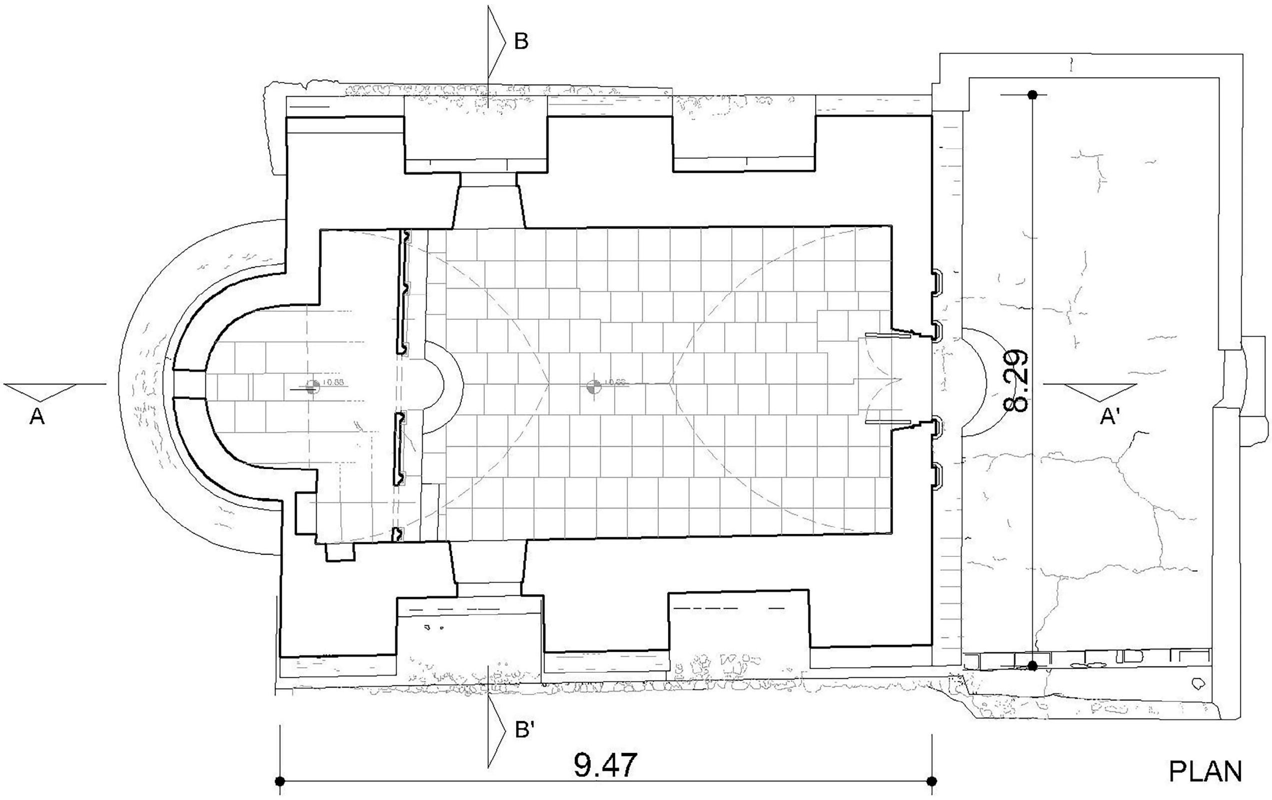

Figure 2. Plan of Saint George Mormoris. A-A′ and B-B′ indicate the trace of two sections.

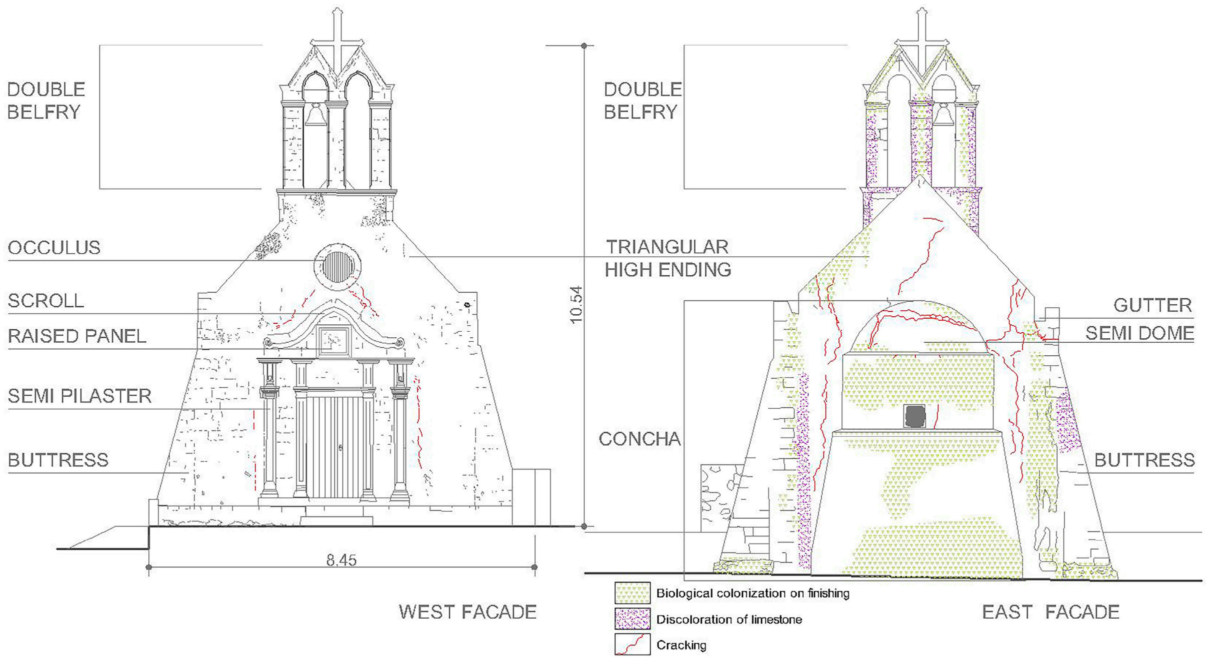

Figure 3. East and west facades of the church.

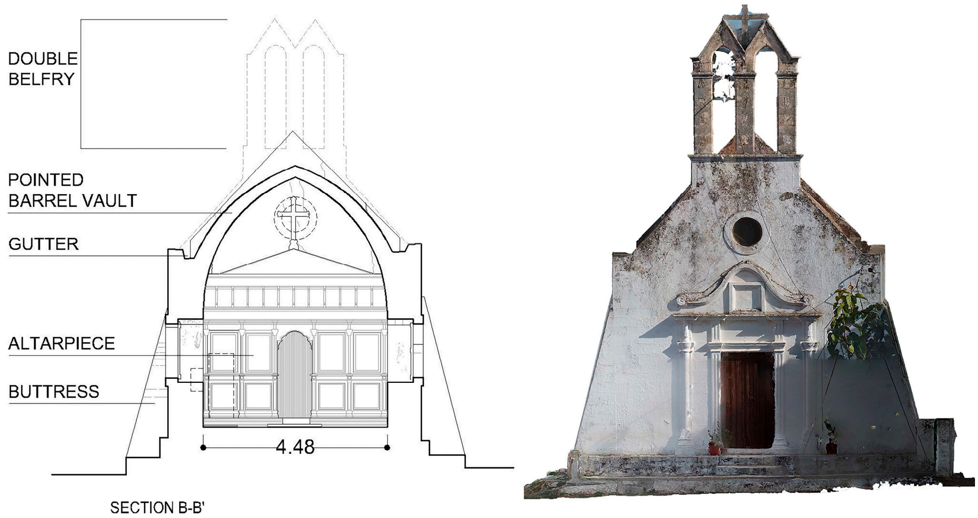

Figure 4. Section B-B′ and west façade with the main entrance (orthophoto).

Six equal-sized buttresses receive the horizontal thrusts (Figure 5) of the pointed barrel vault, with their foundations visible on the eastern side, possibly due to the loss of the outdoor stone paving. The buttresses at the highest points relate to the side walls by the "Γ"-shaped keystone. The western face was probably reconstructed in the middle of the 19th century. Its thickness (0.58 m) makes it thinner than the rest of the masonry. We know from the codex of the Gouvernetou monastery and contractual archives that maintenance work and reconstructions took place in the ecclesiastical glebe in 1848 [22], 1906, 1934, and 1980, according to citizen testimony and the nearby archaeological excavation. In 1982, the monastery was characterized as a protected monument by law [23]. The concha of the church is composed of three parts externally. The base of the concha, being thicker, forms a semicircular conical buttress, there is a main body with a small opening, and there is the higher part of the semi-dome. In the lateral masonry and on either side of the altarpiece, there are two openings with stone arched lintels. The southern opening has a two-arch pointed lintel, and the northern a low-arched lintel, thus strengthening the view of the existence of more than one building phase. In the sanctuary exists the recess of the "prosthesis", which has a relief, while on the side, there is a built-in washbasin. A relief ring runs through the genesis of the dome.

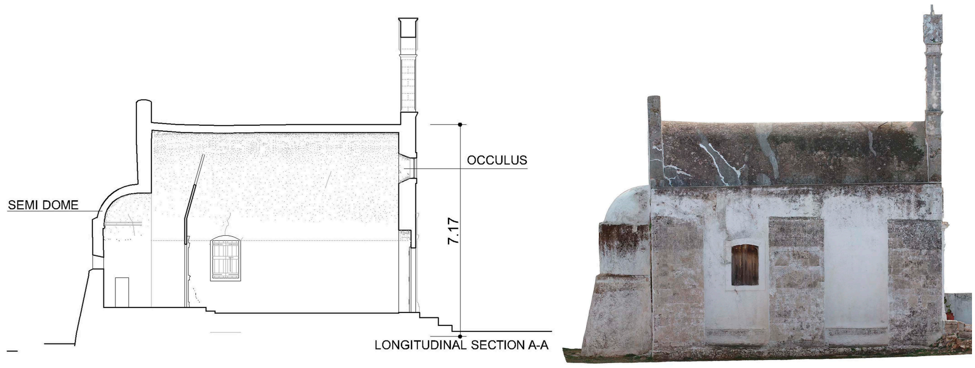

Figure 5. Longitudinal section A-A′, north facade (orthophoto).

Comparing the church (katholikon) with similar ones on the plains south of Chania, we generally observe the following differences and similarities:

- First, buttresses do not often exist on single-aisle churches in that region around Chania except for two churches, which were built in the Venetian period and have non-symmetrical buttresses. This difference probably occurs because the church of Saint George Mormoris has apparently undergone extensive operations.
- Second, by studying the external proportions of the floor plans of single-room churches in the area, it was found that the proportions of length to width were 3 to 2 (1.49/1) [24].

3. Common Damages of Church Structural Parts

3.1. Pathology

In terms of pathology, several factors correlate with the deterioration of the strength of building materials. First, there is the capillary rise of water due to soil moisture through the pores of the masonry, which is associated with the loss of coating and grouting. The main area affected by this phenomenon is the foundation and the base of the structure's masonry walls. Also, low temperatures can cause damage to the structure due to the expansion of the volume of water inside porous stones, with the appearance of cracks. In addition, due to the capillary rise of water where the evaporation takes place, excess salts crystallize inside the pores of the stones or on the surface of the walls. Consequently, this can cause cracks in the stones or concentrations of salts on the surface of the walls [25]. As for the interior space of the churches, high humidity and moisture can cause the growth of mold and the deterioration of the coating and grouting of the masonry [26].

In addition to the above, the influence of environmental conditions can lead to a deterioration of the properties of masonry building materials. The development of biological colonization can accelerate the corrosion of the stones, reducing their strength by creating cracks or by reducing their cross-section. Such deposits can be moss or, generally, any vegetation that can grow on the surface of the masonry. More environmental factors that influence the strength of the structure are differential settlement of the soil and the damage that occurs due to a storm. Differential settlement of the soil usually creates vertical cracks in the masonry walls [27].

The west facade of the Saint George Mormoris church appears to be more deteriorated than the other facades (Figure 3). A similar pathology of biological colonization also appears in the Kaisariani Monastery and is analysed in the study "A Multidisciplinary Approach for Historic Buildings Diagnosis: The Case Study of the Kaisariani Monastery" [28].

3.2. Structural Damages

The main advantage of arched openings and domes built from carved stones is the high compressive strength. The shape of these parts, as well as the location and the type of external load, impact the strength of the structure. For example, the suitable shape of domes and arched openings is parabolic when the forces that are applied are the self-weight of the structure and a small external load. The main factors that cause damage to these parts are the differential settlement, concentrated loads, and dynamic loads due to earthquakes [29]. Especially for the case of differential settlement, the study "Historic Barrel Vaults Undergoing Differential Settlements" provides the experimental results of this mechanism [30].

Arched openings with low height usually present damage in the middle of the arc, while those with higher height usually present damage at three points, with one in the middle and two at an angle of 60°. As for big vaults, the construction of buttresses is required due to the big forces that push the side walls. On the other hand, small vaults create low forces on the side walls, while concurrently, the required thickness of the inner wall is lower [29,31]. The most common damage that occurs in domes is cracking in the middle, where repair can be done relatively easily [29,30].

Additional parts of churches that often present damage are the area of the connection between longitudinal and transverse walls. The main causes of this type of damage are seismic loads and corrosion from water. The main factors that contribute to the presence of damage are the quality of materials and the weak connection between the masonry walls.

Damage often appears on the facade of churches. Usually, cracks appear in the area between the entrance opening and the occulus or the window above it. This crack is usually vertical. In addition, diagonal shear cracks can be present on either side of the entrance opening. The main cause of this damage is the activation of an out-of-plane mechanism due to the seismic loads.

Another critical structural part of churches is the concha. The concha has the main characteristic of stiffness concentrated in a small area. This feature makes it vulnerable to rollover mechanism failure in connection with the masonry of the church [32,33].

The case studies of Brandonisio, Papa, and Clementi describe the damages that were caused to churches by two seismic events in the years 2009 and 2016 in Italy [34–36]. In some cases, there are damages common to the church that will be studied in this paper.

4. Survey

This section develops the work of the church survey into four parts to extract multi-faceted results that demand a multidisciplinary approach.

4.1. Geometry

The survey of the geometry of the church was a complementary study (more precisely) and a correction of the already existing one [15], which had been created during a laboratory exercise by the postgraduate program of the Department of Architecture at the Technical University of Crete during the academic year 2021–2022. This more precise study was needed because the existing structure had to be identified in terms of its fundamental characteristics (natural frequencies, modulus of elasticity, masonry strength) in the computer-simulated model. The particular geometry of the church demanded a combination of methods, namely:

1. Usual surveying with tape measure and digital range finder: the rangefinders used were Laser Leica Disto D2 and Bosch GLM 150;
2. A digital theodolite (Total Station) was used through the application of an open traverse in an independent coordinate system, and the equipment used was the HTS-420R total station;
3. Photogrammetry was used using a drone and a camera to produce orthophotos and a 3D model of the church;
4. Finally, an impression was made using a LEICA laser scanner.

The processing of the primary data of the measurements was carried out using the programs Agisoft Metashape Pro 1.7.4, AUTOCAD 2022, and RHINOCEROS 7.

4.2. In Situ Measurements

Operational modal analysis (OMA) is a method of determining the dynamic characteristics of a structure based on the data collected from micro-vibrations that the structure experiences under its operating conditions [37]. The present method is applicable to particularly bulky constructions, and practically, it is difficult for a device to create a dynamic load. In the OMA method, unknown ambient periodic waves are used to count the characteristics of the structure. Subsequently, raw data are processed by various algorithms to reproduce the dynamic characteristics of the structure fully. In this work, the peak picking (PP) method was used, and for this reason, its basic principles will be briefly analysed. In this method, natural frequencies are determined based on the maxima presented in the frequency spectrum diagram. This method has proven, in many cases, to be reliable and accurate. In the case that the maximum frequencies are presented at a very close distance from each other, the results may still be incorrect. Hence, on a case-by-case basis, the researcher should evaluate the results that are examined. The application of OMA to civil structures generally spans from dynamic identification to continuous dynamic monitoring. This method has been used for the dynamic identification of monuments, such as research on the seismic response of a prestigious masonry palace and the exhibited damage pattern that was retrofitted after the 2009 earthquake in L'Aquila [38]. Also, the resolution of the identified modal parameters in relation to the instrumentation strategy (dense or not dense sensor distribution) and the building's history is discussed in another study on the medieval church of Saint Agata del Mugello, a Cultural Heritage building with a rich and complex constructive history and many repair operations [39].

The equipment used was the SYSCOM [40] company's acceleration measurement system of the Applied Mechanic Laboratory at the Technical University of Crete. In the present study, two recording units and two triaxial sensors were used to carry out the measurements. The locations where the acceleration sensors were placed are shown in Figure 6, next to the two windows on the south and north sides of the church. The sensors were synchronized to start recording at the same time, and the duration of field recording was 10 min.

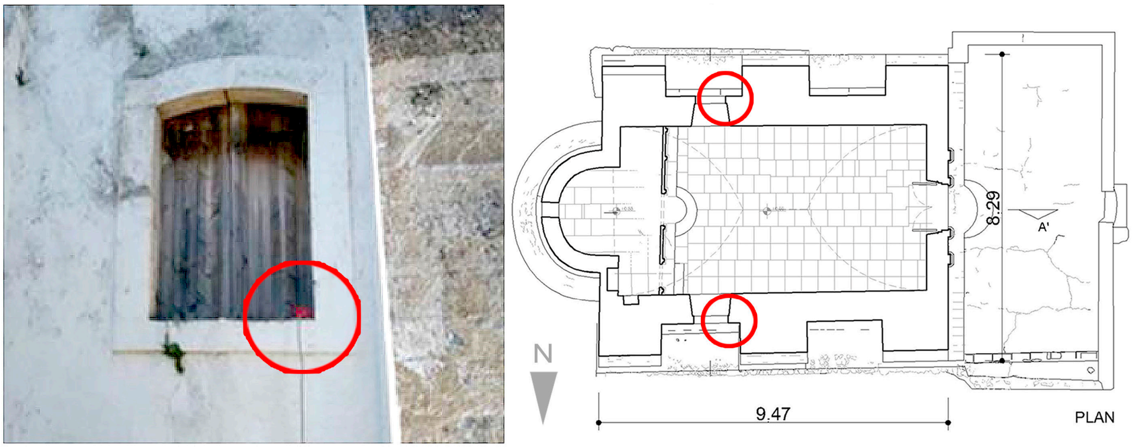

Figure 6. (**Left**): North window with low arch lintel. (**Right**): The position of the sensors in plan and near the windows.

Primary data were imported into the Artemis Testor and Artemis Extractor programs. As a result of the above procedure, the first 14 natural frequencies are presented for the frequency values of 7.63 Hz, 9.95 Hz, 11.57 Hz, 11.98 Hz, 12.33 Hz, 16.15 Hz, 16.41 Hz, 21.35 Hz, 21.89 Hz, 22.31 Hz, 25.99 Hz, 26.41 Hz, 28.62 Hz, and 29.48 Hz (see Table 1 below). These values, in combination with the structural damage that the church presents, were used to support the finite-element model in a preliminary stage of analysis. For the model verification, more accelerometers can be used, and measurements of more places must be recorded.

Table 1. Estimation of the characteristics of masonry.

Strength of Masonry Made of Carved Stones	
Compressible strength of masonry (MPa)	4.98
Modulus of Elasticity (GPa)	4.2
Poisson's ratio v	0.30
Strength of Rubble Masonry	
Compressible strength of masonry (MPa)	2.53
Modulus of Elasticity (GPa)	1.40
Poisson's ratio v	0.30

4.3. Structural Material

To evaluate the physical and mechanical characteristics of the church's masonry, some correlations and assumptions were made in parallel with experimental measurements. Initially, it was assumed that stone and mortar samples taken from the neighbouring buildings of the monastery have similar chemical compositions (resulting from the transdisciplinary academic courses and research that took place in the laboratory of the Department of School of Architecture, Technical University of Crete). The limestone from which the church is built has a consistency of 2.38 g/mL. In addition, the grouting used in the neighbouring constructions turns out to be lime mortar with few hydraulics. The aggregate of the grouting is composed of pyroclastic or quartz sand. The consistency of the grout is estimated at 1.39 g/mL. In addition to the chemical analysis that has been carried out on the church, non-destructive methods have been applied to assess its mechanical properties. The methods applied were impact measurement and ultrasound. In addition, for the final assessment of the mechanical characteristics of the masonry, a correlation was made with that presented in the appendix of Chapter 3 of the KADET regulation [40]. The final values obtained are presented in Table 1.

From the in-situ observations, two main methods of structuring the stone masonry of the church were found (Figure 7). The pseudo-isodome ashlar limestone masonry, measuring approximately 50 cm × 25 cm × 20 cm in each part, and random rubble masonry. The masonry has a maximum thickness of 80 cm, the domes have a thickness of about 26 cm, and the west face is equal to 58 cm.

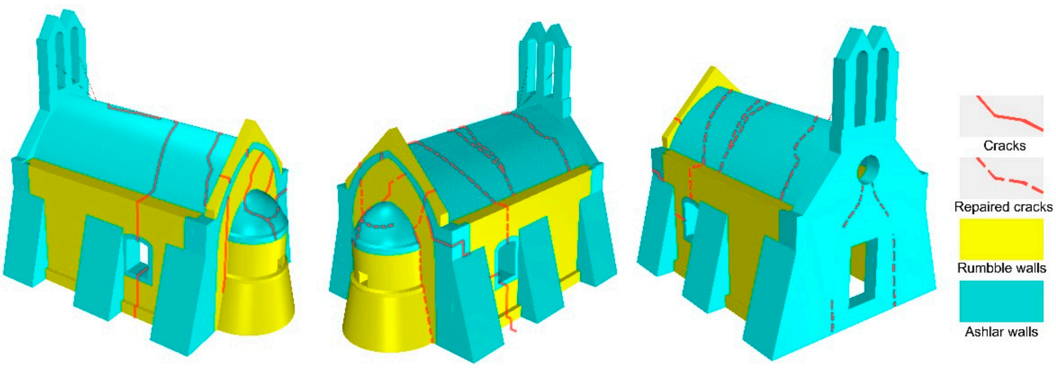

Figure 7. Coloured perspective diagrams of material and damage to the masonry of Saint George Mormoris church.

As we discerned under the colouring, the outer face of the western face with the belfry, possibly the outer faces of the six buttresses, the arched frames of the openings, and the dome of the concha were built with carved limestone. The domes and parts of the thickness of the openings are indirectly found to be made of carved limestone due to the type of cracks, the construction located in the area, or methods of structure that were common during the same time. The limestone structure material was established by sampling and laboratory FTIR testing at the Laboratory of Materials for Cultural Heritage and Modern Building.

The walls in the longitudinal direction, the inner side of the western face, and the base and the body of the concha are made of uncut stones with grouting. This was assumed from the material that has been revealed through the cracks and from older photographic pathology material, as no archaeological research or extensive conservation work has taken place.

4.4. Damage and Cracking

Information about the history of structural damage, as well as the corresponding operations that have been done to the church in the past, were extracted from the Archive of the Ephorate of Byzantine Antiquities of the Prefecture of Chania. These refer to serious moisture problems (1990), cracks in the vault and the walls, damage to bell tower elements, detachments and corrosion to bell tower's metal elements, the existence of subsidence (2007–2018), restoration both externally and internally of the church with the method of stone stitching and the elaboration of exploratory works regarding the foundation of the church to deal with the problems of cracks in the masonry (2007).

The regular colourings and previous piecemeal repairs of the church surfaces make it difficult to understand the failure mechanisms of the stone masonry precisely in the present. The aging of the construction and weather conditions have aggravated the deterioration of the joint mortars. The orthophoto of the top view of the dome shows cracks that also correspond to the interior. The following can be summarized.

- The northeast corner, along with the buttress, is almost detached, with a range of cracks from the top to the foundation, as shown in Figure 8. The active mechanism seems to be a combination of ground subsidence and seismic excitation with a simultaneous overturning tendency. In addition, the failure of the mortar of the gutters causes the accelerated corrosion of the masonry since the water flows into the joints and the local cracks.
- A tendency also to cut off the eastern half of the church in a direction towards the northeast corner is indicated through continuous cracks, as shown in Figures 9–11.
- Cracks and the curvature of eastern masonry indicate that the failure mechanism in the present case is also combinatorial. The seismic loads in the masonry in the east-facing dome find an obstacle in the concha. The result is the vertical faulting of the eastern face along with subsidence in the northeastern buttress corner (Figure 12).

Figure 8. External (photo from 28th Ephorate of Antiquities of Chania, 2007) and internal damage on the northeast corner of the church (2022).

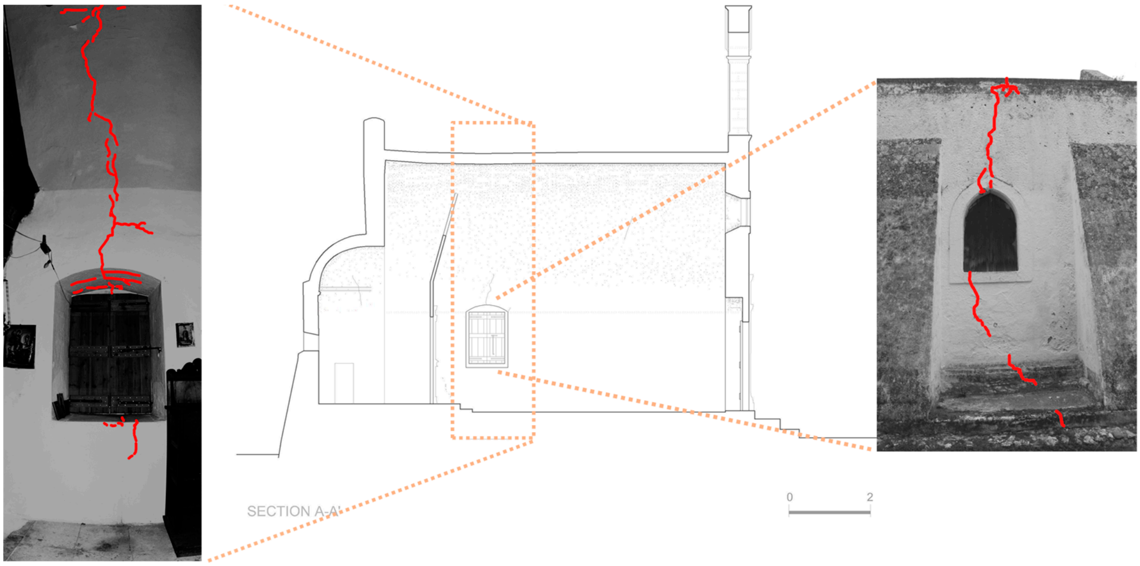

Figure 9. Section A-A′. Internal and external damages on the south wall of the church (2022).

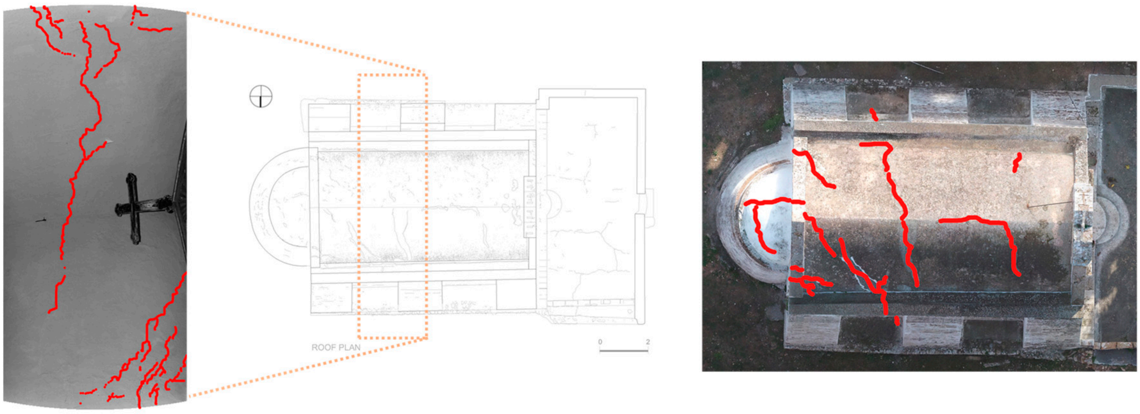

Figure 10. Continuous cracks through the pointed barrel vault (2022).

Figure 11. Internal and external damage to the north masonry of the church (2022).

Figure 12. Damage on the east facade on either side of the concha (2022).

Similar damage and erosion are present in churches that are located in the Chania region: (a) Biological colonization on Saint George's church at Drakena village; (b) Constructive cracking on Prophet Helia's church at Mournies; (c) Rising damp, erosions due to rain, efflorescence, and discoloration on Saint George's church at Vrysses (Figure 13). The type of vault construction can be seen in the vault of Saints George and Nickolaos church (Figure 13).

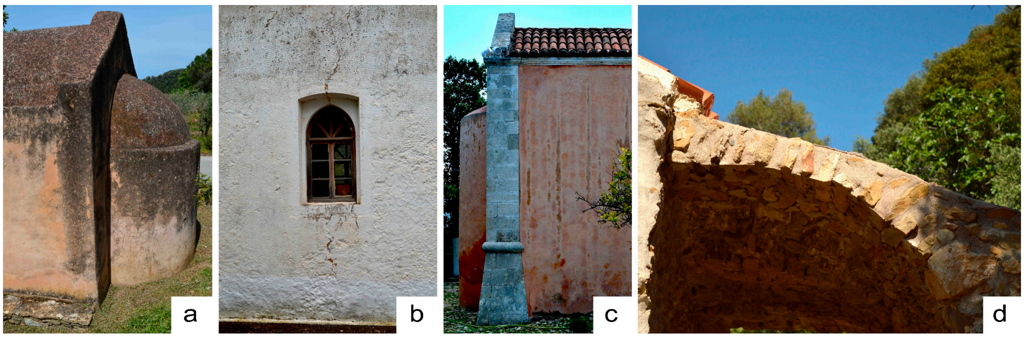

Figure 13. (**a**) Biological colonization on Saint George's church at Drakena village; (**b**) Constructive cracking on Prophet Helia's church at Mournies; (**c**) Moisture problems on Saint George's church at Vrysses; (**d**) Construction detail of dome on Saints George and Nickolaos church (author).

5. Analyses

5.1. Static and Dynamic Loadings

For the spectral analysis, a design spectrum was created according to Greek Regulations, which is in accordance with Eurocode 6 (Figure 14) [41,42]. The soil category was assumed to be Category A, meaning that the structure was founded on rocky soil. In addition, the class of significance of the building was chosen to be IV as the building has a monumental character [43].

Regarding the static loading, the combination of 1G + 0.3Q, where G is the self-weight of the structure and Q = 1 kN/m^2 is the moving loads on the structure, was considered, according to Greek Regulations [41]. For response spectrum analysis, four dynamic load combinations were imposed, considering the vertical component of the earthquake negligible. The results, which are given below, were produced by linear analysis.

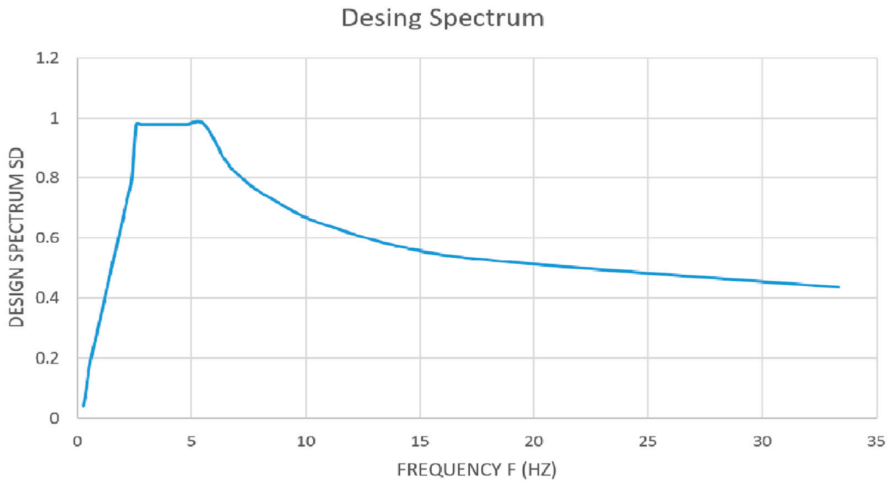

Figure 14. Design spectrum.

In addition to dynamic analysis, research was carried out to correlate the pathology of the structure with the possible existence of differential subsidence on the east side of the church.

5.2. Modelling

The finite-element method was applied to analyse the structure [9,10]. The finite-element method can produce very accurate results for very complicated geometry. Parts of a structure, such as vaults, arched openings, and concha, are very difficult to model with other methods, producing solutions with low accuracy. The structural performance of complicated structures, like churches, and their structural behaviour are evaluated using three-dimensional numerical finite-element models and dynamic identification tests [26].

The first step of the analysis was to draw multiple 3D models of the church with the acceptable designed model, where the finite-element program reads the volumes and the surface form of the structure cleanly and separately. The 3D model of the church was designed in the Rhinoceros CAD program.

In the second step, a model was created consisting of 37,380 three-dimensional finite elements (Figure 15). The finite elements are tetrahedral with four nodes of solid elements (hexahedrons) with three translational degrees of freedom at each node and 0.5 m maximum length of each side of the element. The finite-element mesh was selected after some attempts to achieve the best possible simulation of the real structure and the accuracy of the results since the density of discrimination and the size of the finite elements influence the precision of the final solution of the model. The number of finite elements influences the computational cost. Regarding the boundary conditions, the whole structure supports its gravity loads, and the nodes of the base are fixed with the ground since no signs of slip or movement phenomena exist in the structure. The church was divided into parts that represent the different parts of the structure and can be modelled as flexible contact bodies. Fixed conditions were considered between these contact bodies. The consideration is taken that no unilateral contact phenomena between walls and vault will be developed based on the absence of significant cracks at the connections to the structure. The cracks were also modelled with unilateral contact along specific interfaces, which were assumed at the place where the main cracks exist. Future studies of crack activation will assume that separation and friction effects can be considered across these interfaces.

Because the study takes place at the macro level, it was assumed that the masonry walls are composed of homogeneous and isotropic continuum materials. The study was conducted in the elastic range, which must be considered to be a first, nevertheless significant, step for service conditions.

The third step was to solve the model of the structure for different scenarios of static and dynamic forces. Additionally, multiple scenarios of support conditions, such as differential subsidence, were examined. All the analyses and results described below were calculated digitally in the MSC Marc program.

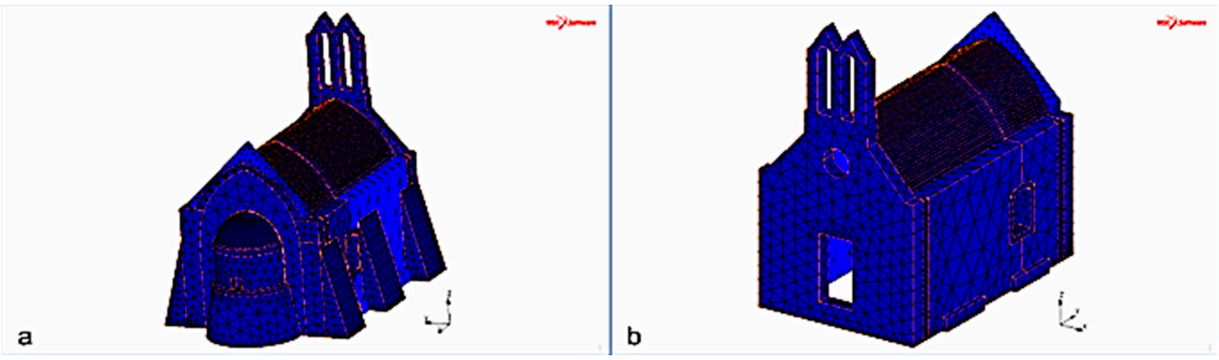

Figure 15. Finite-element model of the church: (**a**) with buttresses; (**b**) without buttresses.

5.3. Modal Analysis

As a result of the modal analysis, the most characteristic eigenfrequencies and eigenmodes of the church were calculated. In particular, the 1st eigenfrequency (7.82 Hz), the 2nd (9.82 Hz), the 11th (22.69 Hz), and the 14th (28.44 Hz) were also recorded by in situ measurements with little deviation. Table 2 summarizes the data from the experimental data, and those calculated from the finite-element model and indicative modes are shown in Figure 16.

Table 2. Summary of the table of natural frequencies from in situ measurements and modal analyses.

Modal Response	Natural Frequencies of Finite-Element Model	Percentage of the Mass Activated			Natural Frequencies from In Situ Measurements
		X	Y	Z	
1	7.87	0.071	3.98	0.04	7.63
2	9.82	75.74	3.99	0.04	9.95
3	13.74	75.92	4.3	0.09	11.57
4	14.27	75.93	4.46	0.09	11.98
5	14.68	75.93	87.65	0.15	12.33
6	17.19	76.75	87.65	0.16	16.15
7	20.37	76.93	89.83	0.25	16.41
8	20.51	79.23	90,01	0.26	21.35
9	21.00	79.23	90.26	0.27	21.89
10	21.71	82.21	90.26	0.27	22.31
11	22.69	92.19	90.27	0.28	25.99
12	25.18	92.19	91.13	0.33	26.41
13	27.31	92.43	91.15	0.34	28.62
14	28.44	93.31	91.15	0.37	29.48
15	28.79	93.43	91.19	0.17	

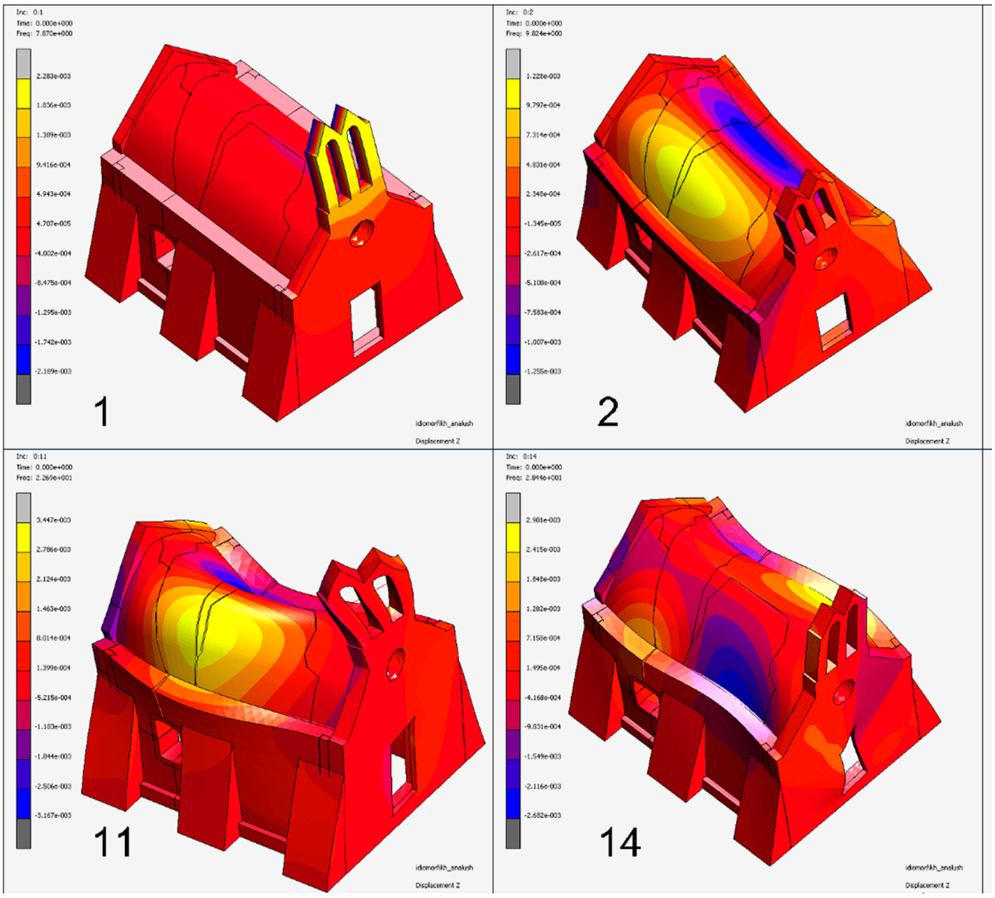

Figure 16. Eigenmodes of the church for the frequencies of 7.87 Hz (Shape 1), 9.82 Hz (Shape 2), 22.69 Hz (Shape 11) and 28.44 Hz (Shape 14).

5.4. Response Spectrum Analysis

The response spectrum analysis was calculated by importing the design spectrum into the finite-element model and taking, in each combination, a different percentage of action of the seismic component. The first 15 modes have been considered in the analysis. Four dynamic load combinations: (1.0 × Ex + 0.3 × Ey), (−1.0 × Ex − 0.3 × Ey), (0.3 × Ex + 1.0 × Ey), and (−0.3 × Ex − 1.0 × Ey) were used, according to the Greek Anti-Seismic Code [41]. The results of the first combination (1.0 × Ex + 0.3 × Ey) correlate with the pathology of the structure. Indicative results of the analysis are presented in Figure 17.

Stress concentrations are presented at points where the structure has been cracked. Most stresses on the dome, as shown in Figure 17, are tensile stresses. The west facade of the dome is stressed by tension and shear. The stress is concentrated at the points where the facade has been cracked. Finally, on the east elevation, shear stresses are concentrated at the corners of the masonry as well as at the base of the triangular ending.

5.5. Subsidence

A principal reason for damage in historic masonry vaults consists of relative displacements of the vault's abutments. Research has been done to understand the nature of the deformations and the complex failure patterns for various settlement configurations [30].

In our study, three different cases of subsidence were considered: (a) subsidence only on the northeast side of the church (Scenario 1), (b) subsidence on both corners of the east side of the church (Scenario 2), and (c) total subsidence on the entire east side of the church (corners and dome, Scenario 3) (Figure 18). In all scenarios, the subsidence was set equal to 2 cm.

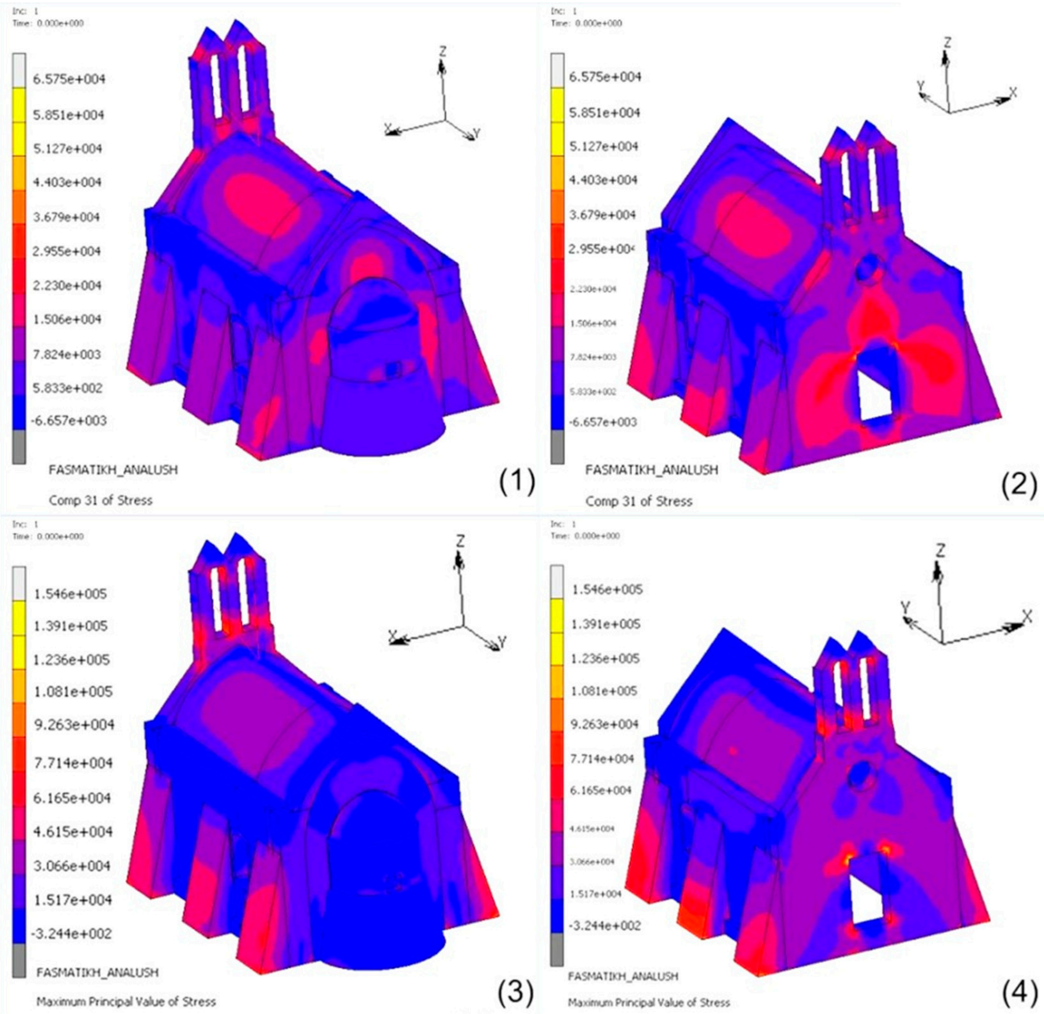

Figure 17. Response spectrum analysis results (Case 1.0 × Ex + 0.3 × Ey): (1) and (2) the shear stress Szx, and (3) and (4) the maximum principal tensile stress (in Pa).

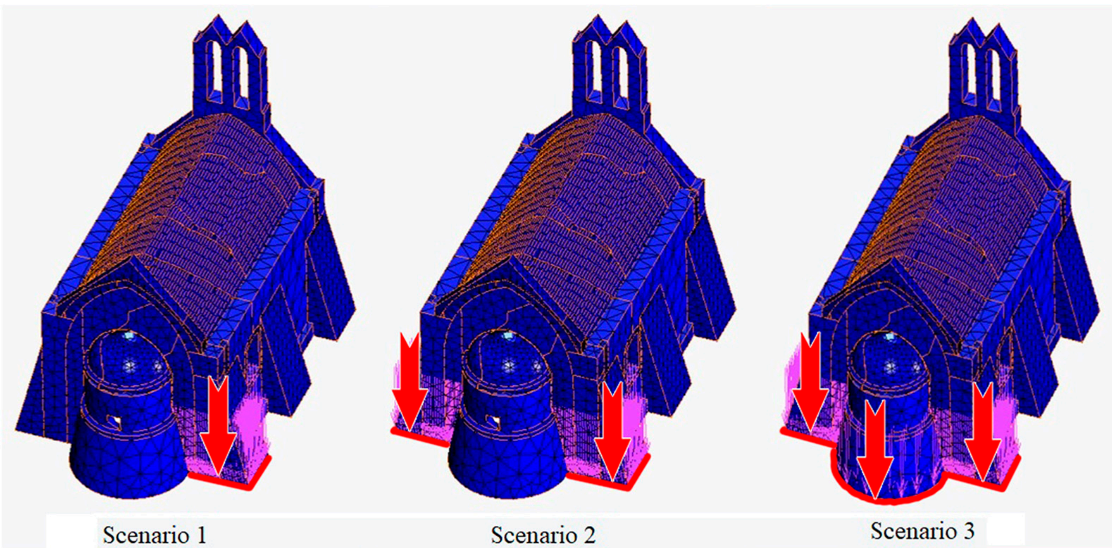

Figure 18. Scenarios of settlement.

Indicative results of the examined scenarios are presented in Figures 19–21. In (1), the out-of-plane movements of the dome are presented (in m); in (2), the distributions of maximum principal tensile stresses on the eastern face of the church are presented (in Pa); and in (3) and (4), the vertical movements of the church are presented (in m).

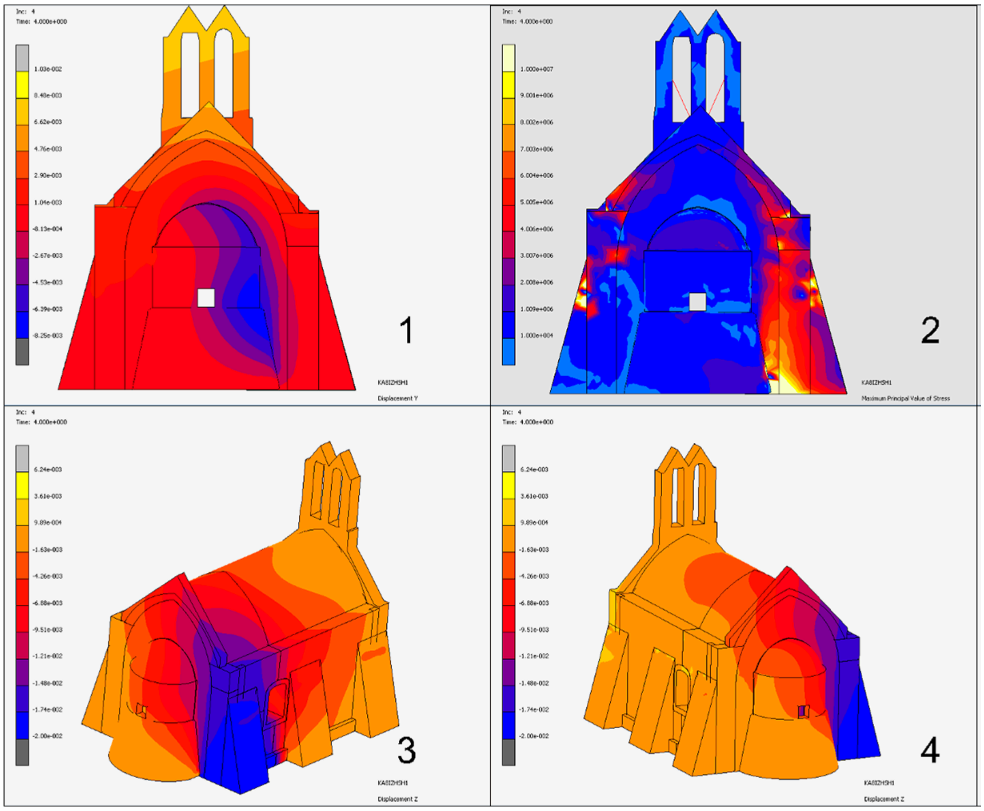

Figure 19. Analysis results for loading Scenario 1.

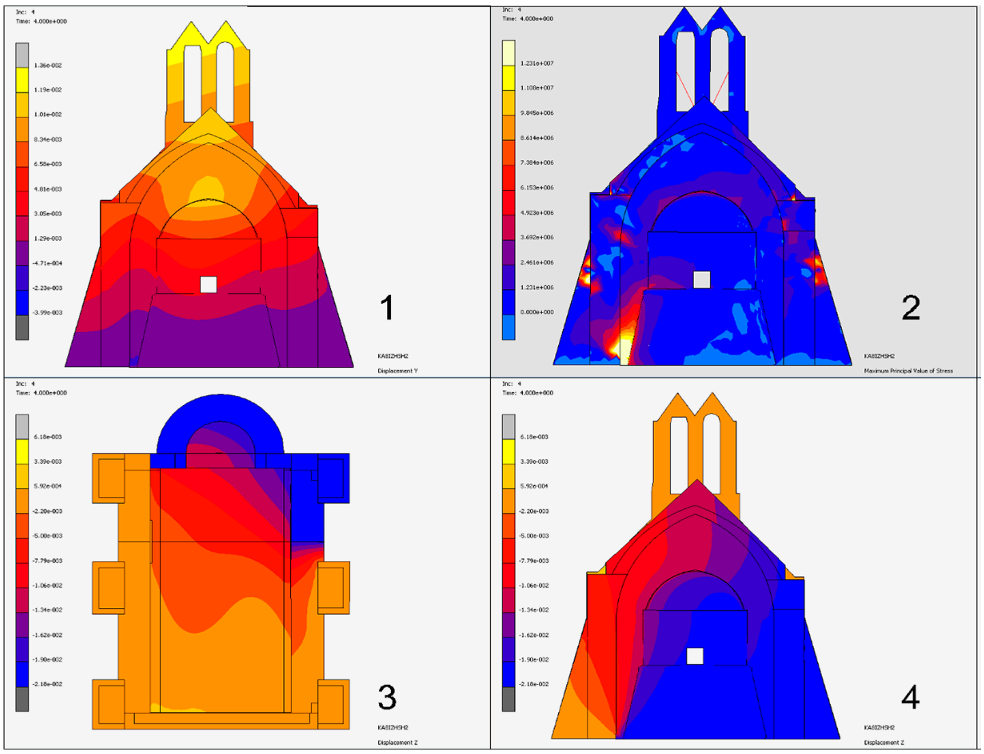

Figure 20. Analysis results for loading Scenario 2.

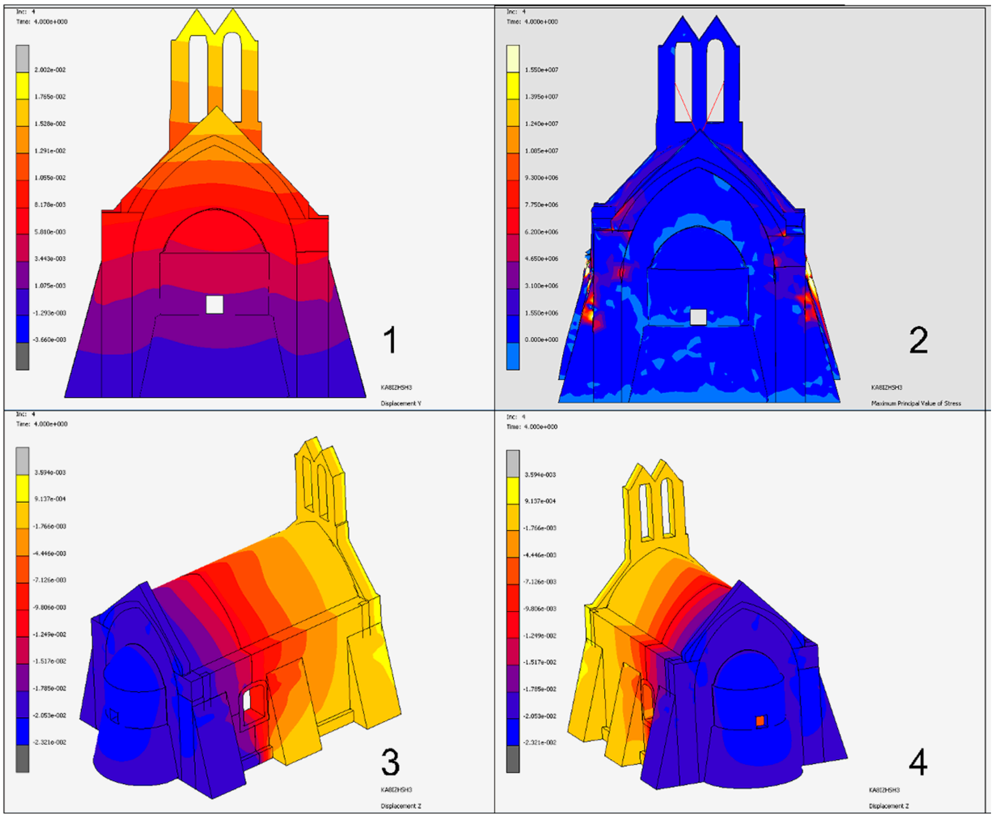

Figure 21. Analysis results for loading Scenario 3.

From a comparison of all the scenarios analysed, the most likely scenario to have taken place is Scenario 2. This scenario presents such a deformation profile, which indicates the concentration of stresses at points close enough to where damage has occurred in the church.

5.6. Seismic Excitation

For the evaluation of the structural behaviour under seismic excitations, the accelerograms of two seismic events were selected and applied to the models in the transient dynamic analysis.

First, the Arkalochori Earthquake, on 27 September 2021, which was a strong earthquake with moment magnitude of 6.0, associated with normal faulting, ruptured the central part of the island of Crete, Greece, at about 20 km to the south of Heraklion. Second, on 17 January 1995, a major earthquake struck near the city of Kobe, Japan, with a moment magnitude of 6.9.

Two models were established and analysed to study the influence of the masonry buttresses on the dynamic behaviour of the structure. From the contour plots of maximum principal stress, the reduction of tension because of the buttresses is shown in Figures 22–24 for both earthquakes. In addition, the stress concentration relates to some of the existing cracks, especially on the eastern wall (Figure 9).

Future work will focus on the study of the activation mechanism of the existing cracks with the modelling of existing cracks with unilateral contact–friction interfaces [12,44].

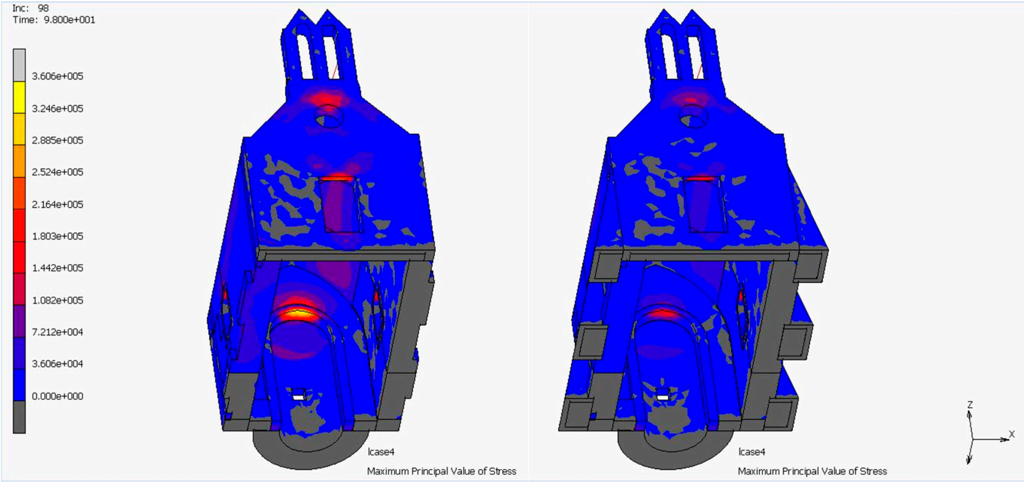

Figure 22. Maximum principal tensile stress for Arkalochori earthquake transient analysis (in Pa) (left without and right with buttresses).

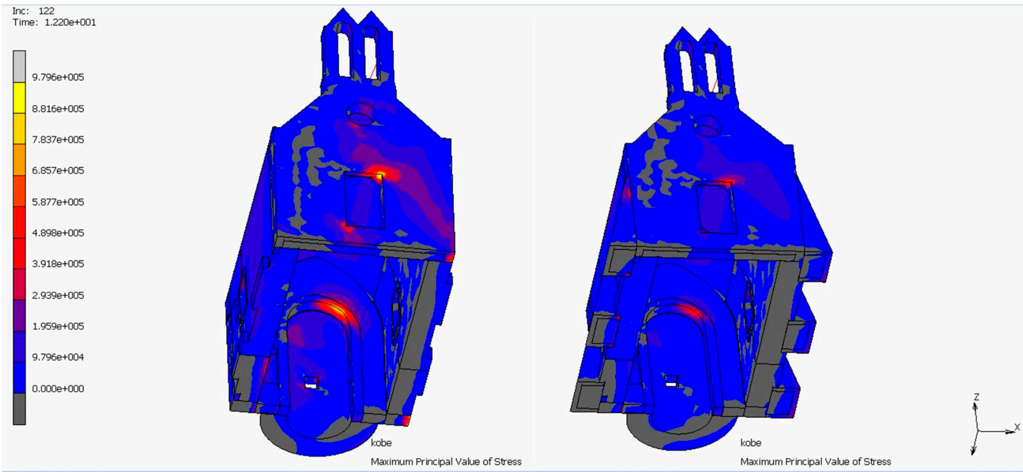

Figure 23. Maximum principal tensile stress for Kobe earthquake transient analysis (in Pa) (left without and right with buttresses).

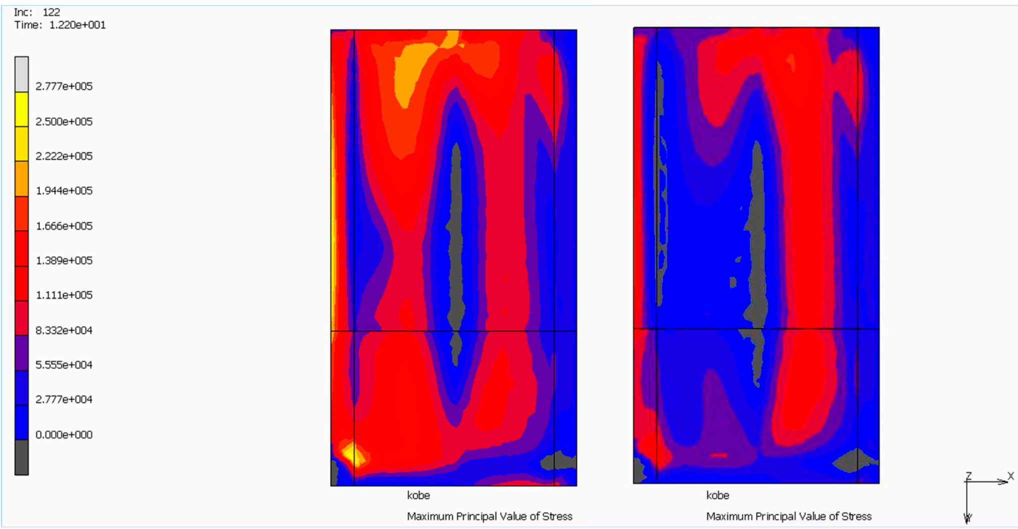

Figure 24. Maximum principal tensile stress for the Kobe earthquake transient analysis (in Pa) (vault top view) (left without and right with buttresses).

6. Conclusions

A detailed finite-element model was used to evaluate the structural behaviour of a masonry Venetian church with a vault. Reasonable assumptions regarding the characteristics of the church were assumed, like the way the structure was founded, the exact mechanical characteristics of the masonry, and the exact determination of the way the masonry of the church was built in some places with the history of the structural damages. In addition, the corrosion and its influence on the final strength of the masonry in an unknown parameter were explored.

The influence of specific structural parts of the structure, like masonry buttresses and wall connections, on the structural behaviour was examined through a response spectrum analysis, the static analysis for subsidence of some parts, and the transient analysis of two specific seismic excitations. The comparison of the model analysis results with a structural pathology led to the identification of the causes of the damage to the church since the concentrations of stresses due to dynamic loading and subsidence are almost identical to the areas of damage. This study was conducted in the elastic range, which must be considered to be a first, nevertheless significant, step for evaluating structural strength under service conditions.

The church was divided into parts, which represent the different parts of the structure and the locations of the main cracks. These are modelled as flexible contact bodies, and fixed conditions were considered. Future studies of crack activation will assume that separations and friction effects can be considered across these interfaces.

Considering all these damages in a time series, a classification could be as follows:

1. Initially, the main cause of the weakening of the support is the erosion of the masonry due to weathering;
2. Possibly, some dynamic loadings that had an acceleration of that of the design dynamic load or even greater caused the first cracks;
3. The gradual removal of the soil around the east side of the church due to rainwater runoff probably caused minor subsidence in the structure, causing the corresponding crack damage.

From the above study, important conclusions can be extracted about the role of their structural elements. The existence of buttresses to strengthen the longitudinal walls of the church improves their behaviour against out-of-plane bending.

A compliant restoration method in terms of building methods and materials could be suggested as defined by the Venice Charter of 1967.

1. Archaeological research and excavation to uncover new evidence;
2. Excavation of the foundation for autopsy and then deciding how to strengthen it either using piles or by adding reinforced concrete beams;
3. Use of joint mortars of the same composition as existing ones, limestone of the same dimensions, stone jointing (with stones and metal plates);
4. Soil filling beneath the concha is approximately 0.50 m;
5. Maintain and recover old gutters according to the trace on the wall;
6. Restoration of belfry;
7. Colour restoration on the exterior, with priority to preserving the existing colour traces, based on witness reports.

The proposed method starts with the creation of a reliable structural model, which compares well with the measured eigenmodal data and the documented damages. At the material level, stones and mortar were investigated experimentally. The mechanical properties of the mixture comprising the masonry structure have been estimated using results from the literature and used further for structural analysis. A comparison of modal analysis was based on microtremor measurements of the real structure and the appropriate postprocessing of measurements. The comparison was satisfactory for many frequencies of interest.

Modal and response spectrum analysis is based on linearly elastic behaviour. Nonlinearity is being considered indirectly through modified design spectra. This is the best that can be done for reliable evaluation of monuments at the structural level. The use of nonlinear time history analysis with suitable earthquakes is, in principle, possible, although finding reliable nonlinear material data is difficult. Therefore, useful results would have required extensive parametric investigation with many possible material data and earthquakes.

A detailed finite-element model, as has been used in the paper, is able to provide predictions for both the seismic behaviour of the whole structure and its vulnerable structural members. The complexity of the monumental structure and the need to investigate many parameters and collect geometric, historical, architectural, and structural data lead to the need for an interdisciplinary approach to the structural study regardless of its scale. The main conclusions concerning complex structures are generalized to all composite structures with similar geometrical elements, where parts of different stiffness cooperate and damage results from combined actions.

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