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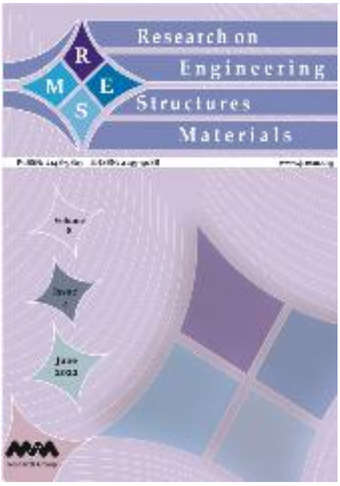

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Online Publication Date: 10 May 2023

URL: http://www.jresm.org/archive/resm2023.641ea0305.html

DOI: http://dx.doi.org/10.17515/resm2023.641ea0305

Journal Abbreviation: *Res. Eng. Struct. Mater.*

To cite this article

Bilgin H, Fule Z, Ozmen HB. Numerical study to evaluate the structural response of the basilica of St. Sotiri. *Res. Eng. Struct. Mater.*, 2023; 9(2): 309-329.

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Research Article

Numerical study to evaluate the structural response of the basilica of St. Sotiri

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Article Info

Article history:

Received 05 Mar 2023
Revised 16 Apr 2023
Accepted 06 May 2023

Keywords:

Basilica-type churches; Dynamic analysis; Finite Element modeling; Monumental buildings UNESCO

Abstract

Basilicas constructed in the post-Byzantine time in Balkans cover a period of 400 years, from the 16th century to the 19th century. These masonry religious objects are of particular interest due to their different building typologies and historical value, so it is important that they be saved for future generations. This paper analyses the static and dynamic response of the Basilica of St. Sotiri near Gjirokastër (Albania). The static response and dynamic properties of the church have been assessed using FEM technique and the performance of the structure is investigated. As a result, important information is obtained to identify the critical regions of the structure and its seismic safety. The aim of this study is to point out that clear insight and information on interpreting the actual response of historical buildings can be obtained by numerical analysis methods. Authors believe that the approach and findings of this case study are useful to understand the load response of a wide range of monumental churches.

1. Introduction

The number of historical monumental structures in Europe and worldwide is huge. They are encountered in many seismic regions of the world in different states of integrity, ranging from undamaged to near -almost ruined. Nowadays, in Albania there are encountered many historical monuments which show masonry construction techniques that varies from century to century [1]. Starting from ancient structures such as Apollo Temple constructed during 5th century B.C in Apollonia, a large number of castles such as Gjirokastra's Castle, Rozafa Castle in Shkodra, Berat's Castle dating between 14th -16th century A.C, and a large number of churches, basilicas, monasteries and mosques are found throughout Albania [2]. During the past century, due to historical and political events that happened in the country, these buildings were almost forgotten, and no maintenance was done in order to preserve these cultural heritage buildings and rescue them from deterioration and amortization [3]. Some of them were able to continue to exist till today and the others were lost in the course of time partly by man-made actions and previous natural catastrophes [2].

Churches, mosques, city walls, castles, and clock towers built in various parts of the world are the key shapes of monumental ancient buildings [4-6]. They characterize a significant part of the Balkan cultural heritage, mainly vulnerable and prone to partial or complete failure under seismic loads as noted in some of the recent earthquakes in the region (Bosnia and Herzegovina-1969; Italy-1976; Montenegro-1979; Albania-2019) [7, 8]. These monuments are one of the most important key elements of our cultural diversity and preservation and restoration of them are essential engineering concern and duty to

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DOI: http://dx.doi.org/10.17515/resm2023.641ea0305

guarantee the sustainable advancement and safety of our cultural funds to pass them onto upcoming generations [9-11].

An important portion of the Albanian cultural heritage is derived from the church masonry structures. The majority are in their original locations; most of them are still not in use [3]. However, natural or man-made hazards pose a severe threat to their survival [12]. Limitations in the ability to inspect the building or difficulties in extracting samples from buildings of historical value often caused restricted knowledge of the internal structure system or the properties of available materials. In addition, deterioration of material resistance and avoidance of deterioration are often witnessed throughout the life of ancient structures [13].

These historical buildings carry significant info to historical incidents, characters, history development, etc. [14-16]. They play a vital role in defining periods of engineering and architecture throughout history, including the advancement of construction techniques, ornamental patterns, building materials, and many other related topics [13].

Many of these structures deserve a specific structural analysis to evaluate their safety level under both static and dynamic loads. Also, the information obtained by the analyses of the individual structures may be used to determine more general interpretations about similar historical structures. In this regard, the aim of this paper is to bring into focus a historical basilica church from Gjirokastra which is a historical city remarkable for its great beauty, as well as its harmonious intercultural mix of Albanian, Byzantine and Ottoman heritage. The Church of the St. Sotiri's Basilica is selected to investigate its structural performance (Photo 1).

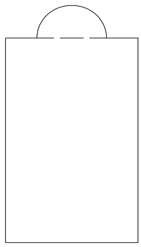
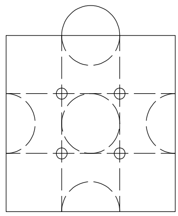
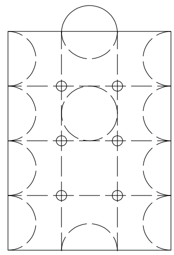
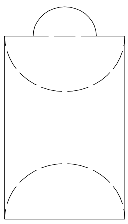
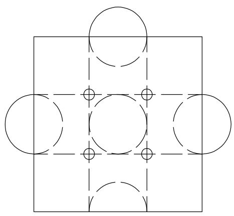
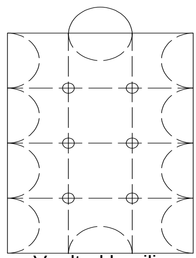
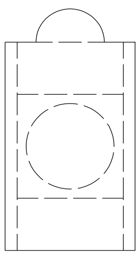
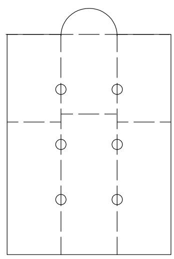
Photo 1. Church of the St. Sotiri's Basilica

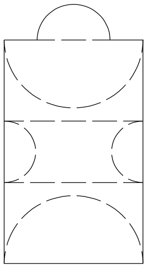
It is one of the most remarkable religious monuments in the Gjirokastra district and is a type of three aisled barrel-vaulted basilica composed of the nave, the altar and the sanctuary which are composed in the same space dating back to the 17th-18th century. Firstly, current conditions of the structure are examined by in-situ inspection. Secondly, a global analysis of the structure has been prepared by utilizing the finite element (FE) modelling method. Then, the obtained results were compared with the visual inspection observations made on the load-bearing components of the church. It is believed that the findings could provide a case study that expands the understanding of the structural behavior of this structure typology. Considering its historical value, building developments, public and religious status make this study an important and interesting issue.

2. Church Types in Post-Byzantine Period

There are possible ways of classification based on different features of historical masonry structures. Material type, strength and stiffness of sections and the construction techniques are major properties of structural form. Typological classification contributes to the development of post-Byzantine architecture in time and space, the features that characterize this architecture in different periods and regions, the preference of certain types and forms in these periods, and the relationship between them. In classification, the criteria used in the study of Byzantine architecture and mainly based on plan and spatial composition are followed. (Table 1), [17].

Table 1. Classification of the churches in post-Byzantine period

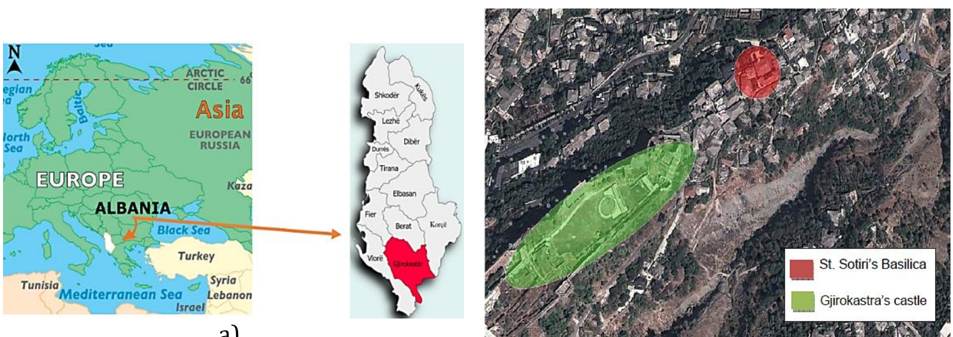
Type / Version	Single-Naved (T1)	Cross-in Squared (T2)	Basilicas (T3)
Version-1	 Single nave	 Cross-in-square single-apse	 Domed basilica
Version-2	 Single nave barrel vaulted	 Cross-in-square tri-conch	 Vaulted basilica
Version-3	 Domed single-nave		 Flat interior ceiling basilica
Type / Version	Single-Naved (T1)	Cross-in Squared (T2)	Basilicas (T3)

Version-4	 Cruciform roof

First, the type is defined according to the plan composition; Single Nave, Domed Square Cross churches and basilicas. The spatial composition of the interior, which is a very important component of the psychological and aesthetic understanding of religious buildings, helps to define different categories within each type. Thus, the first category of the first type includes churches without interior ceilings; the second category is churches with barrel vaulted interiors; the third category includes churches with or without vertically varying interiors with a central dome on a pulley; The fourth category includes churches whose interior lining system looks like a cross from the outside. The second type of the domed square-cross church is a very unified type when it comes to interior spatial composition. In this type, there are two categories in which plan differences affect the interior composition: churches with one apse and churches with three apses. Basilicas can be classified into three categories. The first category consists of domed basilicas (domes on a high drum). The second category includes basilicas whose interiors are covered with a system of vaults or curved structures. The third category is basilicas with flat ceilings [17].

2.1. Description of the St. Soitiri's Basilica

The St. Soitiri's Basilica is situated in the Old Bazaar beneath the great Castle of Gjirokastra, a city with a population of around 43000, notable for its great natural magnificence, as well as its harmonious inter-cultural mix of Albanian, Byzantine and Ottoman culture (Figure 1a-b). It was built in 1784 which used to be the seat of the local Orthodox bishop.



a) b)

Figure 1. a) Location of the studied territory in Albanian map; b) Arial view of the castle and basilica

This study aims to assess the structural response of the church of the St. Sotiri's Basilica (Figure 2). Current situations of the church were studied by in-situ survey. The church is a three aisled barrel-vaulted basilica, with inner dimensions of 15.75 x 12.10 m and it is composed of the nave, the altar and the sanctuary which are composed in the same space. St. Sotiri basilica falls in the type T3V2 of basilica's classification (Table 1).

a)

b)

Figure 2. a) East view of the Basilica; b) Iconostasis

Columns are connected to each other with two main arches that separate the central aisle from the side aisles. In the nave the aisles are covered with cylindrical vaults all along the length. The central space is composed of big vaults and side space of vaults. The altar is composed of three chambers. The narthex is divided into two levels, located at the west side of the basilica and it is separated from the nave by a series of arches. The eastern couple of columns and western couple of columns are thick square based columns and they are connected with transversal arches by creating the altar in the east and the narthex on the west.

The structural inspection of the church includes measurements of length and thickness of structural elements. The thickness of the load bearing walls is 1.0 meter. Sizes of the columns are 500 mm x 500 mm for the rectangular ones and 500 mm diameter for circular base columns. The thickness of vaults and arches are 300 mm. The height of the load bearing walls is 8.0 m. The heights of the columns are 4.6 m., and the maximum height of the basilica is 9.50 m, whereas the outer dimension of the structure is 17.60 m x 14.80 m. Plan view of the case study structure is given in Figure 3.

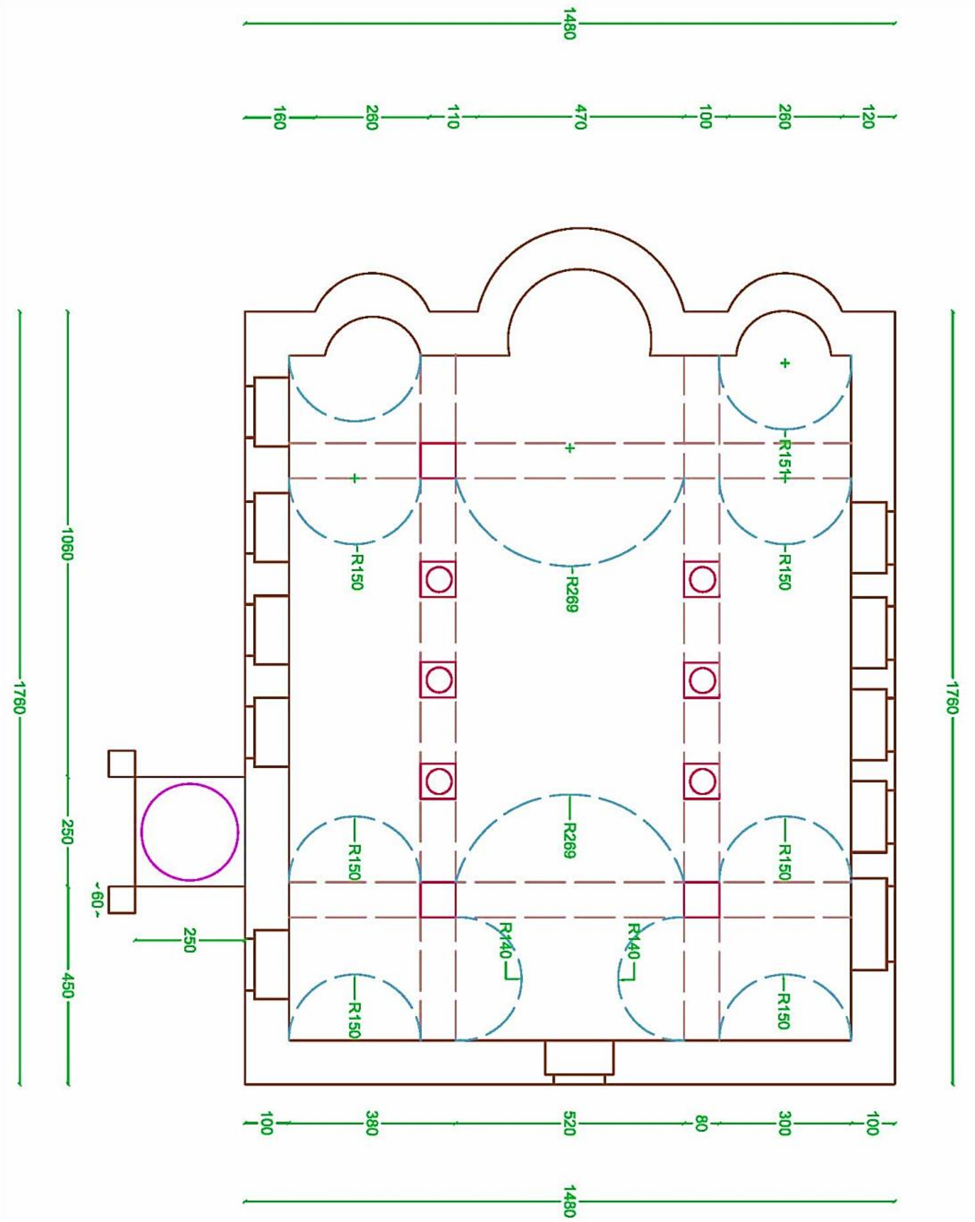


Figure 3. Plan view of the St. Sotiri's Basilica (Units in cm)

The narthex is divided into two levels. The eastern and western couple of columns are thick square (500 x 500 mm) based columns and they are connected with transversal arches by creating the altar in the east and the narthex on the west. In the basilica, there are three main parallel barrel type vaults which are placed in east-west direction, whereas two smaller vaults are constructed to the main ones in the north-east direction.

3. Damage Survey

On-site examination plays a crucial role in the structural evaluation of historical monumental structures, which aims to define the building's condition and describe a typical structural model [13].

In 1999 after an earthquake a slight misalignment and damage to the load-bearing walls occurred. The epicenter of the earthquake was 3.5 km from Gjirokastra, with a magnitude of 4.6 Richter scale and it is recorded by church authorities in basilica's archives. After repairing some parts of the load bearing walls of the basilica, it was added also the tower bell (Photo 2).

Photo 2. Church of the St. Sotiri's Basilica

The walls are reinforced with steel anchors passing from North to South direction. There are 8 steel anchors placed in two rows, four by four, and passing through the piers (they work as tensile members). Inherent material characteristics of the steel tie rods are reflected in the analytical model as given in Table 2.

Table 2. Material properties of steel tie rods

Characteristics	Steel tie rod
Modulus of Elasticity, E (GPa)	181.7
Poisson's Ratio	0.3
Tensile Strength (MPa)	542.3
Yield Strength (MPa)	363.2

As the geometrical characteristics of the basilica are determined, the structure is investigated on-site, and cracks and other irregularities are detected. Due to the architectural renovations, structural deficiencies cannot be identified easily. However, through the site checks, some of the cracks could be visualized.

In St. Sotiri Basilica, lime mortar is used in masonry walls. Lime mortar is composed of lime and sand, mixed with water and it has very large durability which is best shown in stillstanding ancient masonry structures. There is no uniformity in the distribution of mortar (Figure 4). In some places it is totally missing, and it is noticed that these places are rebuilt lately (Figure 5).

Figure 4. Western wall of the Basilica (left); Different colored stones, Eastern wall of the Basilica (right)

Figure 5. Northern wall

The middle three couples of columns have circular section while the outer columns have rectangular section.

There are three main parallel barrel type vaults which are placed in East – West direction. Then there are two other barrel type vaults with smaller dimensions, constructed perpendicular to the main ones, placed in North - South direction. From the inspection it resulted that the moisture is a significant problem especially during the rainy season (Figure 6).

Figure 6. Barrel vault over the South aisle, moisture concentration

The narthex is composed of two floors inside the basilica, located at the west side (Figure 7). In St. Sotiris Basilica the narthex is composed of two floors constructed with timber beams in the west side of the basilica and it is separated from the nave by a series of arches.

Figure 7. Narthex, Western side of the basilica

The nave and the side aisles are separated by a series of arches. The nave is covered with a barrel vault. The aisles are located on the sides of the Basilica. It can be found also in the west part of basilica in the role of narthex but in St. Sotiri Basilica they are found on the North and South sides. They are separated by the nave by a series of columns and arches above them.

4. Mathematical Modeling

4.1 Finite Element Modeling

As briefly mentioned formerly, determining the earthquake behavior of historic masonry structures is a challenging job for reasonable effects such as inadequate characterization of the inherent mechanical characteristics of the material, problems in mathematical modeling, and intricate architectural plans [18]. In technical literature, some physical models have been suggested to accurately predict the behavior of masonry material adopting numerous approaches [19].

Mathematical modeling is an important step in the analysis of monumental structures. The 3-D FE (finite element) model created by SAP2000 [20] is deployed using a set of finite elements. Considering the availability of resources, a modeling method should be chosen to define the state of safety of the building to be restored. Figure 8 illustrates three modeling approaches for modeling masonry structures.

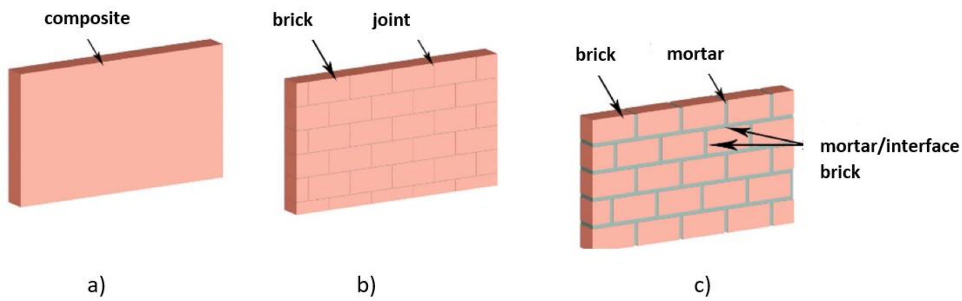


Figure 8. Modelling techniques of masonry: a) Macro modelling; b) simplified micro modelling; and c) micro modelling [19].

In this study, a simplified geometry of the church was adopted by following the macro-modeling technique since it is mostly used for analyzing large-scale structures and the effect of global factors. Such an approach was followed by several researchers [15]. The description of the geometry was accomplished through architectural plans and site measurements. The numerical model consists of main load-bearing volume as shown in Figure 9.

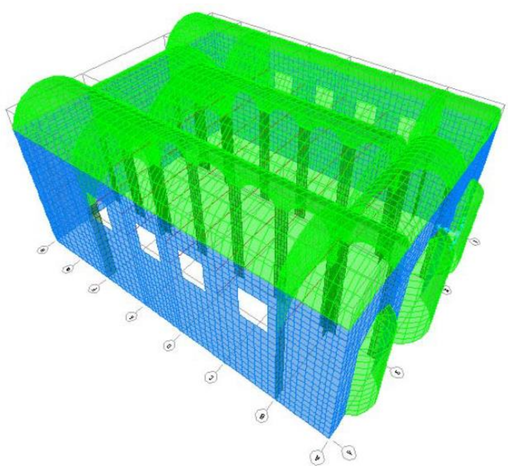


Figure 9. Three-dimensional finite element model of the Basilica St. Sotiri

5. Structural Assessment

Several methods and computational tools are available for the assessment of the mechanical response and current condition of the masonry structures. These methods use different theories or approaches, resulting in different levels of complexity, different costs, and different requirements [21]. The results of the different approaches may also be somewhat different. However, a complex analysis will not necessarily provide us always with better results than applying simplified approaches [18]. The method must be selected based on the chosen numerical model for the structure. A correct structural assessment should be based on a deep data of the following [21]:

- Building history and evolution,
- Geometry,
- Structural details,
- Material properties and construction techniques,
- Crack pattern and material decay map,
- Structural stability,

which can be accomplished through on-site measurements and investigation structural analysis with appropriate models and final diagnosis.

The research work for the material properties of the historical buildings in Albania was not satisfactory. There is a lack of information and laboratory tests, and there are limited possibilities to conduct experimental tests in order to determine the material properties and mechanical behavior of the masonry units. It is not easy to take specimens directly from the historical buildings for testing due to practical safety and official reasons to prevent further damage. In this case, research was made to find the appropriate data to be used in the FE model. Since the Basilica is constructed with tuff masonry, the research is focused on the mechanical properties of this material. Different experimental data are processed to calculate mean values of mechanical parameters of tuff masonry (Table 3).

Table 3. Material properties from previous studies

Properties	Betti et al., [22]	Lourenço et al., [19]	Portioli et al., [23]	Guler et al., [24]
Unit Weight, γ (kg/m^3)	21	17	19	17
Modulus of Elasticity, E (MPa)	1740	1100	900	1000
Tensile Strength (MPa)	0.165	-	0.21	-
Compressive Strength (MPa)	1.7	-	2.1	-

Table 4. Selected material properties

Characteristics	Tuff masonry
Unit Weight, γ (kN/m3)	19.0
Modulus of Elasticity, E (MPa)	1100
Poisson's Ratio	0.071
Allowable Compressive Strength (MPa)	1.700
Allowable Tensile Strength (MPa)	0.165
Allowable Shear Strength (MPa)	0.530

The identification of the typology and characteristics of the material is used to associate it with the mechanical characteristics outlined in an assumed table, which is compiled based on the experimental data in the relevant literature (Table 4).

The other features in this research are the allowable compressive, tensile strength, and shear strength. Based on those physical characteristics, the Basilica structure is analyzed and checked for drawing final conclusions (Table 5).

Table 5. Selected allowable stresses

Allowable compressive stress (N/mm²)	**Allowable tensile stress (N/mm²)**	**Allowable shear stress (N/mm²)**
1.700	0.165	0.530

The dynamic analysis of the Basilica involves the response spectrum which is selected based on EC-8 with 0.25g acceleration, as presented in Figure 10.

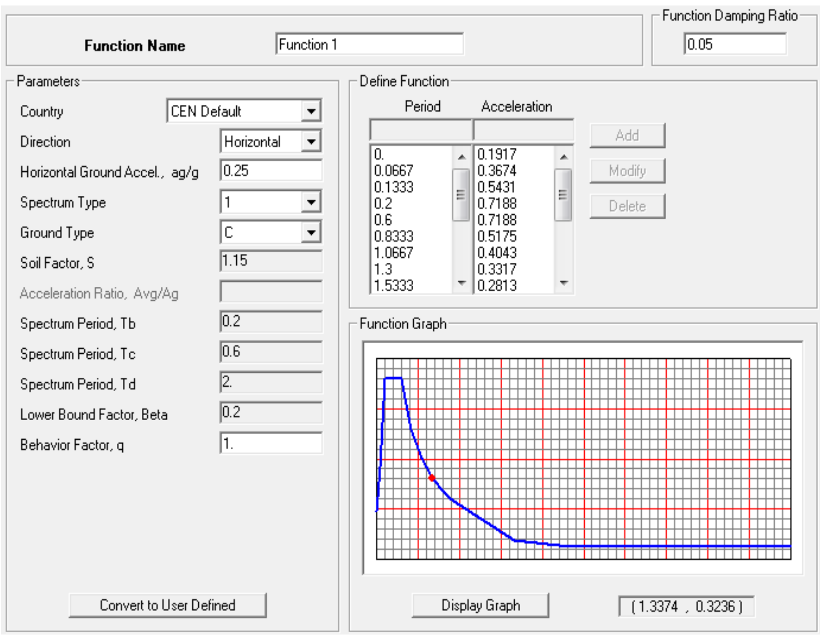


Figure 10. Response spectrum function

6. Results and Discussion

This part includes the analysis of stresses under static and dynamic loads. Linear analysis was used in this study. Static loads are characterized by the dead load of the building or its own weight, while dynamic loads are simulated by seismic loads represented by response spectrum function. All results are highly dependent on the macro modeling stage of the basilica.

For the Basilica St. Sotiri's analysis, two different loading conditions were considered, namely gravity load in x- and y- directions, and G+EQ$_x$ and G+EQ$_y$ for earthquake load, respectively. These loading conditions comprise of the dead load (self-weight) of the structure and the seismic load defined by the response spectrum function for both orthogonal directions.

Firstly, the model has been subjected to vertical loads coming from masonry own weight. To check the deformation of the structure and the concentration of stresses, it is performed a linear static analysis with only dead load or in other terms, self-weight of the structure.

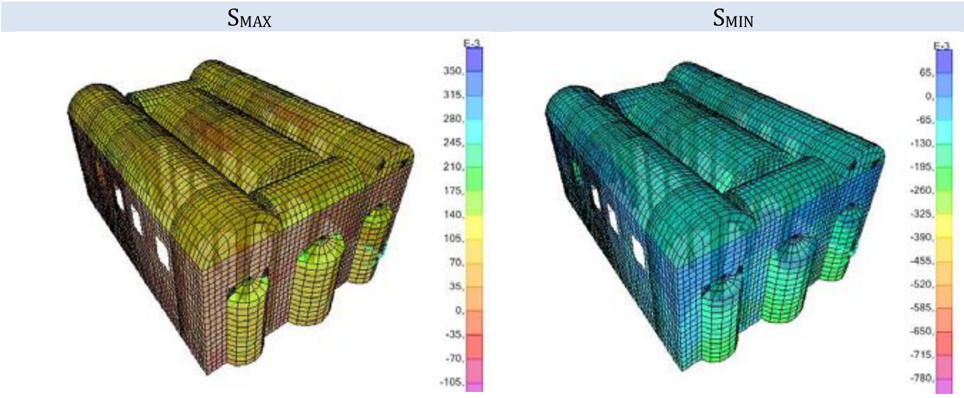


Figure 11. S_{MAX} and S_{MIN} Stresses diagram, (MPa)

The maximum values of S_{MAX} and S_{MIN} are seen at the top of the vaults and Northern and Eastern load bearing walls. The values of S_{MAX} and S_{MIN} are 0.349 MPa and 0.126 MPa for compressive stresses (Figure 11).

The basilica exhibits the maximum displacement at the top of the middle vault:

– -3 mm in X direction
– 2.9 mm in Y direction
– 2.5 mm in –Z direction.

Stresses under the dead load are below the allowable capacity which means they do not exceed the allowable limits. In the main vault over the nave, the stresses S_{MAX} and S_{MIN} are spread on the top of the vault.

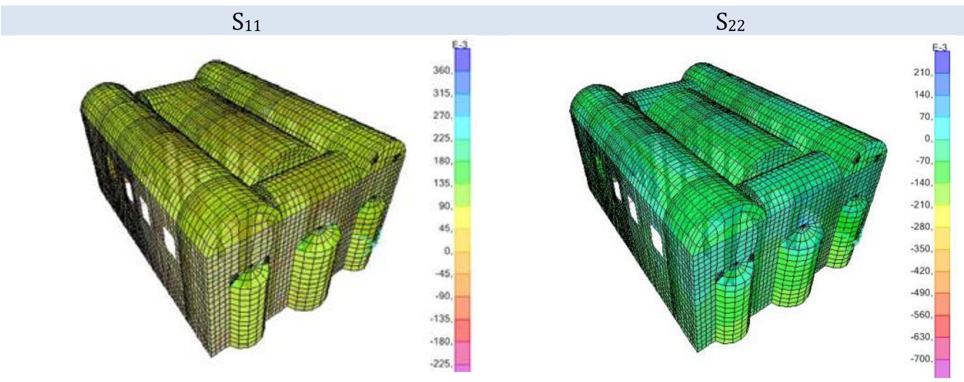


Figure 12. S_{11} and S_{22} stress diagrams under dead load, (MPa)

In the load bearing walls the S_{11} stresses vary from -0,227 MPa to 0,254 MPa. S_{22} stresses vary from -0.753 to 0.233 MPa (Figure 12). The most critical locations are the Northern and Southern load bearing walls which exhibit maximum concentration of stress.

The most potential danger on this structure comes from the S_{MAX} which may cause the structure to develop structural cracks and damages due to increasing tensile stresses. The locations of these concentrations of stresses are in the connection of vaults and load bearing walls, top of the main vault over the nave and in Eastern and Northern load bearing walls.

6.1 Modal Eigenvector Analysis Results

Eigenvector analysis determines the undamped free-vibration mode shapes and frequencies of the system. It is used FEM to perform this analysis because the basilica has a complicated geometry. These natural modes provide a good insight into the behavior of the structure.

Table 6. Modal characteristics

Mode Number	Period	U_X	U_Y	U_Z
1	0.242	8.981E-07	0.70494	5.913E-07
2	0.180	0.650	4.744E-07	0.00025
3	0.170	4.194E-08	0.0279	1.595E-07
4	0.169	0.000004	0.00102	3.909E-08
5	0.166	5.207E-08	0.00068	9.5E-10
6	0.165	0.000044	1.495E-07	0.000035
7	0.163	0.000071	3.792E-09	3.398E-08
8	0.162	3.484E-08	1.352E-08	2.218E-08
9	0.122	0.00039	0.000001	0.00925
10	0.122	0.000002	0.00163	0.000022
11	0.113	3.866E-08	0.00641	9.634E-07
12	0.111	1.95E-07	0.0049	8.327E-09

Table 6 summarizes the first twelve modal shapes obtained from modal eigenvector analysis. The 1st mode shape of the basilica involves the translation along the weakest transversal direction, with significant out-of-plane deformation of the orthogonal components. Figure 13 shows the first five modal shapes derived from modal eigenvector analysis.

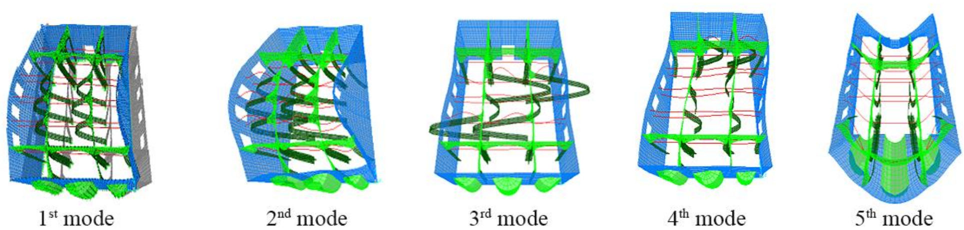


Figure 13. Modal shapes of the structure

6.2 Response Spectrum Analysis Results

Then, for more detailed results Basilica St. For Sotiri's analysis, two different loading conditions were considered, namely gravity load in x- and y- directions, and G + EQ_x and

G+EQ_y for earthquake load, respectively. These loading conditions comprise of the dead load (self-weight) of the structure and the seismic load defined by the response spectrum function for both orthogonal directions.

The considered element stresses are identified as S_{11}, S_{22}, S_{12}, S_{13}, and S_{23}. Shell internal stresses are reported for both the top and the bottom of the shell element. The top and bottom of the element are defined relative to the local 3-axis of the element. The positive 3-axis side of the element is considered to be the top of the element. The internal stresses and axes used in the definition of the shell element can be seen below Figure 14.

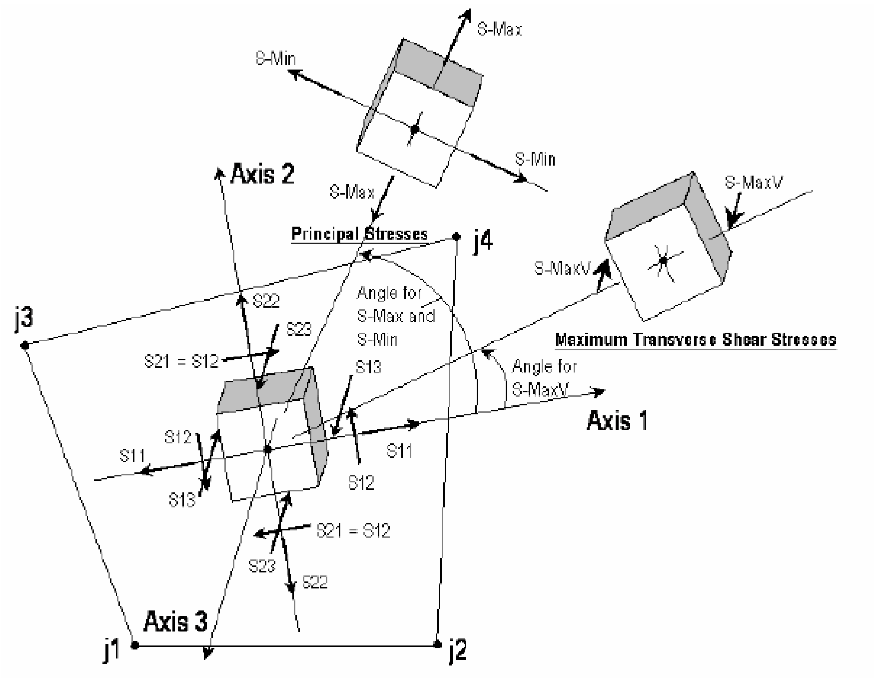


Figure 14. Internal stresses in shell element [20]

- S_{11}, stress acting on the positive and negative 1 face in the 1-axis direction - Hoop stress.
- S_{22}, stress acting on the positive and negative 2 faces in the 2-axis direction - Radial stress.
- S_{12}, shearing stress acting on the positive and negative 1 face in the 2-axis direction and acting on the positive and negative 2 faces in the 1-axis direction.
- S_{MAX}, maximum principal stress.
- S_{MIN}, minimum principal stress. By definition, principal stresses (S_{MAX} and S_{MIN}) are oriented such that the associated shearing stress is zero.
- S_{13}, Out-of-plane shearing stress acting on the positive and negative 1 face in the 3-axis direction.
- S_{23}; Out-of-plane shearing stress acting on the positive and negative 2 faces in the 3-axis direction.

$G+EQ_x$	$G+EQ_y$

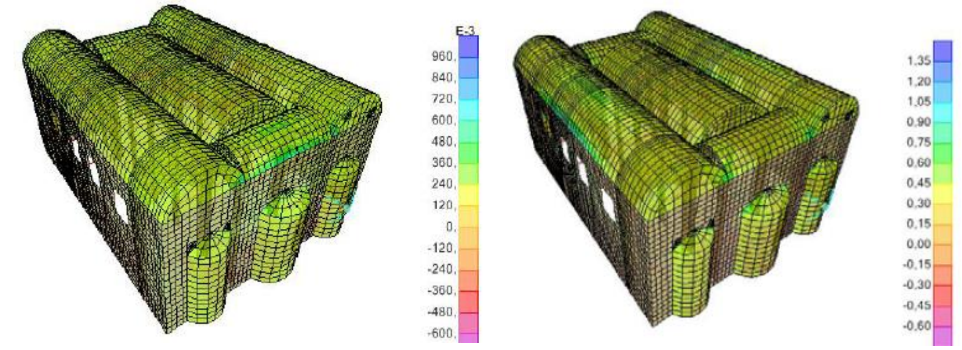


Figure 15. S_{22} tensile stresses distribution, (MPa)

$G+EQ_x$	$G+EQ_y$

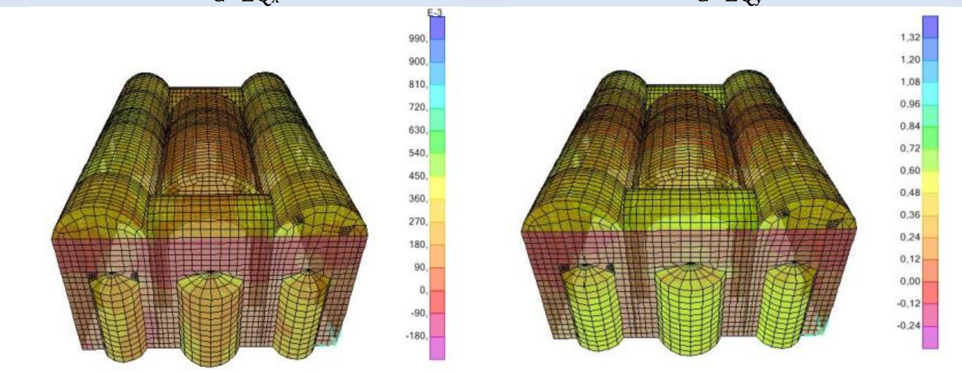


Figure 16. S_{12} tensile stresses distribution, (MPa)

S_{12} and S_{22} stresses for $G+EQ_x$ and $G+EQ_y$ loading cases acquired (Figure 15-17) at structural elements of the St. Sotiri's basilica are shown in Table 7-8.

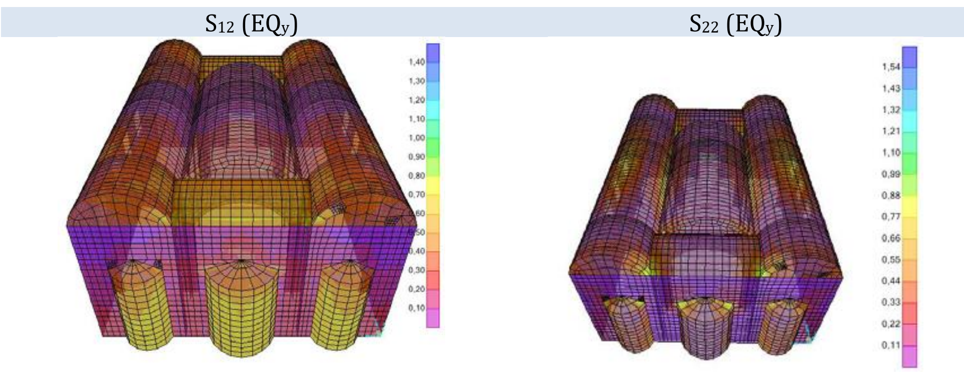
Table 7. S_{12} and S_{22} stresses for the structural elements

Structural Elements				S_{12} $G+Eq_x$ (MPa)	S_{12} $G+Eq_y$ (MPa)	S_{22} $G+Eq_x$ (MPa)	S_{22} $G+Eq_y$ (MPa)
Vaults	Nave	Top surface	Tension	0.910	0.025	0.366	0.204
			Compression	0.259	0.027	0.306	0.388
		Bottom surface	Tension	0.416	0.015	0.303	0.426
			Compression	0.460	0.030	0.319	0.337
	Aisles	Top surface	Tension	0.268	0.019	0.088	0.221
			Compression	0.215	0.020	0.074	0.193
		Bottom surface	Tension	0.204	0.019	0.047	0.133
			Compression	0.219	0.028	0.015	0.151
	Narthex	Top surface	Tension	0.422	0.095	0.125	0.435
			Compression	0.402	0.047	0.098	0.356

		Bottom surface	Tension	0.356	0.193	0.046	0.269
			Compression	0.369	0.187	0.035	0.259
	Sanctuary	Top surface	Tension	0.460	0.221	0.047	0.303
			Compression	0.204	0.219	0.019	0.088
		Bottom surface	Tension	0.305	0.388	0.015	0.221
			Compression	0.225	0.303	0.011	0.234
Load bearing walls	N-S Walls	Top surface	Tension	0.356	0.015	0.027	0.059
			Compression	0.303	0.193	0.460	0.047
		Bottom surface	Tension	0.435	0.088	0.015	0.019
			Compression	0.409	0.047	0.193	0.088
	E-W Walls	Top surface	Tension	0.027	0.025	0.388	0.027
			Compression	0.021	0.221	0.303	0.204
		Bottom surface	Tension	0.035	0.460	0.256	0.185
			Compression	0.029	0.431	0.204	0.221
Columns	Columns	Top surface	Tension	0.303	0.219	0.439	0.015
			Compression	0.299	0.221	0.428	0.388
		Bottom surface	Tension	0.435	0.204	0.460	0.303
			Compression	0.420	0.027	0.419	0.299

Table 8. Maximum and minimum stresses due to G+EQ$_x$ and G+EQ$_y$

	G+Eq$_x$ (MPa)		**G+Eq$_y$ (MPa)**	
	Max	Min	Max	Min
S$_{11}$	1.248	-0.205	2.194	-0.143
S$_{22}$	1.015	-0.610	1.413	-0.726
S$_{12}$	0.959	-0.259	1.388	-0.286
S$_{13}$	0.131	-0.017	0.124	-0.015
S$_{23}$	0.196	-0.033	0.139	-0.026



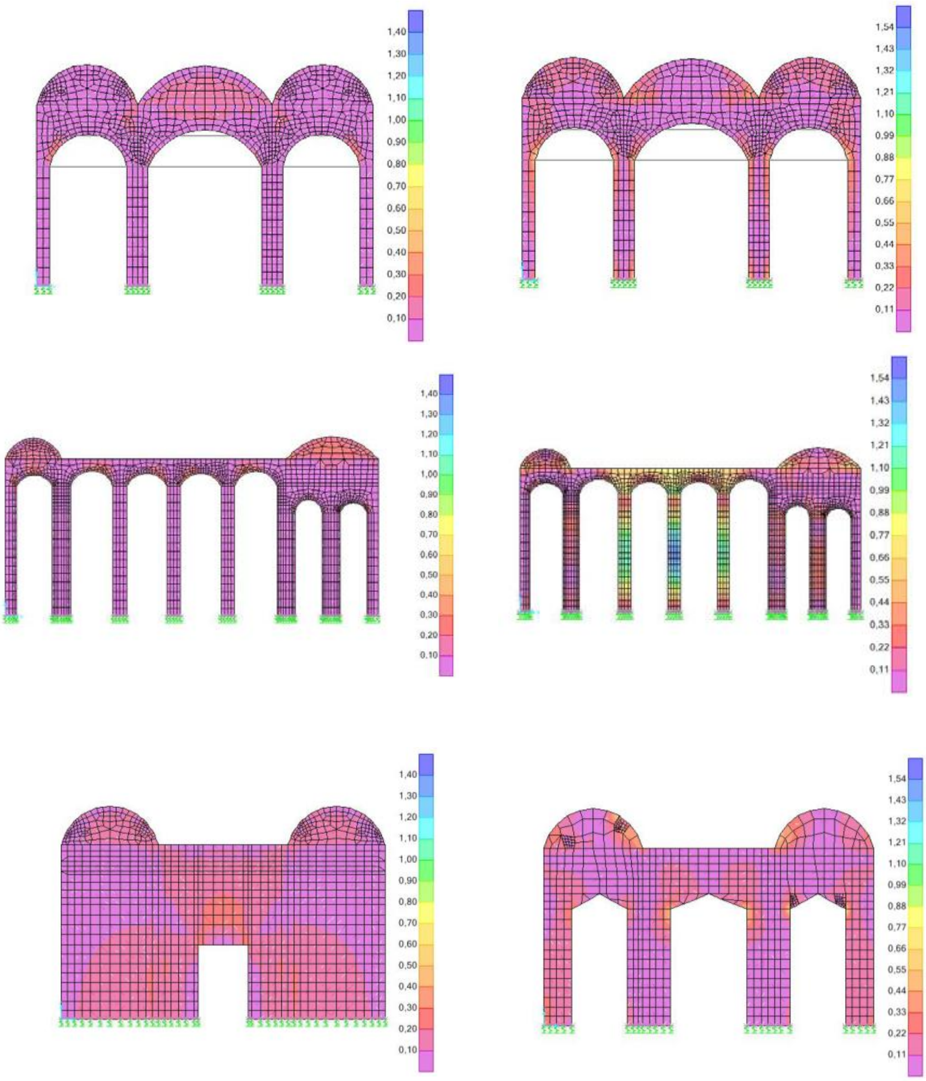


Figure 17. S_{12} and S_{22} for EQ_y loading case, (MPa)

The maximum displacement occurs at x- direction 7.5 mm when applying $G+EQ_x$ load case and at y- direction 11.8 mm when applying $G+EQ_y$ Load case (Table 9).

Table 9. Maximum and minimum stresses due to $G+EQ_x$ and $G+EQ_y$

EQ Load	Displacement (X-direction)	Displacement (Y-direction)
$G+EQ_x$	7.5 mm	6.5 mm
$G+EQ_y$	9.5 mm	11.8 mm

This value of displacement that occurs when applying the response spectrum analysis shows that the basilica is more prone to be damaged if the earthquake direction is along the y- axis. Also, this result matches the real situation of the basilica. The most damages, cracks, misalignment of load bearing walls which are observed, are along the y- axis (N-S direction).

7. Conclusions

In this study, the structural response evaluation of the St. Sotiri Basilica is discussed. The methodology used in evaluation of the structure is visual inspection and simple measurement techniques of the entire structure and determination of the damaged structural members.

From the condition assessment of the St. Sotiri Basilica, it has been observed several damages to the load bearing walls, structural and non-structural cracks, humidity, misalignment, deterioration of surface plaster in vaults, deterioration of steel mechanical anchors etc. The most problematic part of the church is its roof which causes a leakage of water to the vaults and the walls beneath it. It is suggested to repair the damaged elements of the roof and the stone tiles urgently.

To have a better identification of stress distribution, FEM is prepared. Modeling is based on geometric data stored by the Historic Monuments Preservation Institute. Some of the missing data were substituted and assumed from other studies with similar geometrical properties. For analytical modeling, the macro-modeling approach is used. In other words, the results depend on the modeling of the structure.

The FEM prepared by SAP2000 involved assumed material properties due to inability to conduct tests. The maximum displacement obtained from the analysis shows a value of 7.5 mm for $G+EQ_x$ and 11.8 mm for $G+EQ_y$.

The results of the stresses in the basilica system exceed the allowable limits in various levels defined in the study. The findings provided by finite element analysis results support the observations regarding the damage conditions through visual inspections. The analysis of the structure using SAP 2000 has shown that the structure is safe under gravity loads, but it is not safe under seismic loading. The response spectrum analysis has shown that the assumed allowable strength of the materials is exceeded in vaults, Northern and Southern load bearing walls because of high concentration of stresses.

Since this study was based on the material properties and construction period obtained from different research and studies similar to this structure, St. The analysis of Sotiri Basilica can be done using real data that can be found through different laboratory tests and experiments. In addition, nonlinear analyzes can be performed for similar structural monuments after all data and tests, including foundation and soil properties, have been collected. Furthermore, this study proposes that various approaches for the analysis of historical monumental buildings should be compared to cover the inevitable unknowns that may affect the response of materials and mechanics.

Funding Declaration

The authors received no financial support for the research, authorship, and/or publication of this article.

Conflict of Interest

The authors have no affiliation with any organization with a direct or indirect financial interest in the subject matter discussed in the manuscript.

Acknowledgement

HB and HBO made the conceptualization and designed the analysis; ZF collected the data; HB and HBO contributed data and analysis tools; HB and ZF performed the analysis; HB and HBO wrote the paper.

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