Structural analysis of post-byzantine churches: a case study for southern Albania

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ABSTRACT

Hundreds of masonry churches have been constructed in Albania during hundreds of years. The majority of them exist at their original location; a significant part of them are not in use any more. In this context, Roman and post - Byzantine masonry churches attract the world's special attention to this region. It is necessary to carry out systematic studies to assess an inventory and determine the state of masonry churches in Albania, to preserve them, to strengthen their basic structural elements, the arch, vault and other constructive components and soundly deliver them into the future. From this point of view, this study is aims to outline the classification of the churches built in post-Byzantine period based on the plan and spatial composition of these structures. Following this typological classification, the church of the "Monastery of Saint Nicholas" is selected as a case to investigate its structural performance. The church of the Monastery of Saint Nicholas is a domed single-nave church dating back to the 16th-17th century. This church is situated inside a monastery complex and it is proclaimed a monument of culture by Institute of Monuments of Culture Albania.

INTRODUCTION

Albania has been the cradle of many civilizations throughout the history as a result of its location. Each civilization had left its physical signs in the form of small objects to large scale buildings and sometimes even to almost complete cities. Some of the remains of the past have been able to survive until our time and the others have been lost in the course of time partly by human activities and other natural disasters.

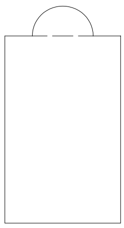
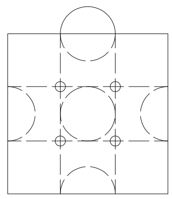
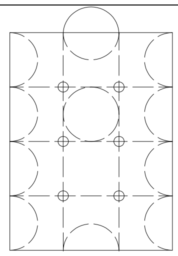
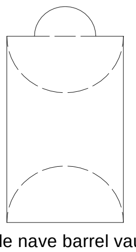
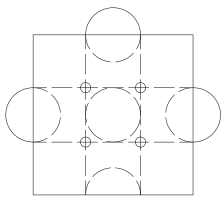
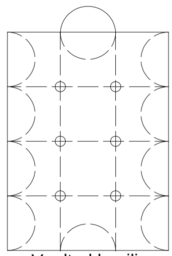
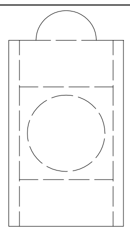
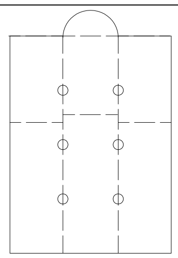
The country has many historical buildings from various civilizations including churches, clock towers and mosques. A large portion of the Albanian cultural heritage is provided by church masonry building. The majority of them exist at their original location; a significant part of them are not still in use. However, natural or man-made hazards cause a serious risk for their survival. These buildings are the major points for the continuity of history to the future.

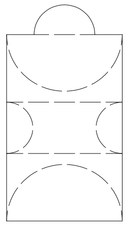
From this point of view, this study presents the classification of post of post-Byzantine churches in Albania based on the plan and spatial composition of these structures. After that, depending upon this typological classification, the Church of the Monastery of Saint Nicholas has been selected as a case to investigate its structural performance. Existing conditions of the building were investigated by in-situ survey. The church of the Monastery of Saint Nicholas in the village of Dhiver, Albania, is one of the most noteworthy ecclesiastical monuments in the Sarande province and is a domed single-nave church dating back to the 16^{th}-17^{th} century. This church is situated inside a monastery complex and it is proclaimed a monument of culture by Institute of Monuments of Culture Albania.

1 TYPOLOGICAL CLASSIFICATION

The typological classification helps to follow the development of post-byzantine architecture in time and space, the particularities that characterized this architecture in different periods and regions, the preference for certain types and forms in these periods and regions, their inter-relation, etc. The classification generally follows the criteria used in the study of byzantine architecture, which are mainly based on plan and spatial composition (Table 1.), [16].

Table 1. Typological classification of the churches

Type / Version	Single Nave (T_1)	Cross-in Square (T_2)	Basilicas (T_3)
V_1	 Single nave	 Cross-in-square single-apse	 Domed basilica
V_2	 Single nave barrel vaulted	 Cross-in-square tri-conch	 Vaulted basilica
V_3	 Domed single-nave		 Flat interior ceiling basilica

V_4	 Cruciform roof		

The type is defined first of all on the basis of plan composition; single nave, domed cross-in-square churches and basilicas. Spatial composition, especially of the interior space, which is such an important component of the psychological and aesthetic conception of religious buildings, helps define the different categories within each type. Thus, the first category of the first type comprises churches with no interior ceiling (the internal roof structure is visible); second category comprises those churches whose interior space is covered by barrel-vault; third category comprises those churches whose interior space changes vertically through a central dome over a drum or not; fourth category comprises those churches whose interior covering system is also visible from outside as a cruciform roof [16].

The second type of church, cross-in-square with dome is a much unified type as far as interior spatial composition is concerned. There are two categories within this type, where differences in plan have influenced the composition of the interior space: single-apse churches and three-apse churches.

The basilicas may be categorized in three categories. The first category comprises the domed basilicas (with dome on high drum). The second category comprises those basilicas whose interior spaces are covered by a system of vaults or curved structures. The third category comprises those basilicas whose interior space is covered by flat ceiling.

DESCRIPTION OF CASE STUDY BUILDING: THE CHURCH OF THE MONASTERY OF SAINT NICHOLA

This study aims to investigate the structural performance of the church of the monastery of St. Nicholas, whose typological characteristics fall in the classification of the domed single-nave churches. The church of the Monastery of Saint Nicholas is a domed single-nave church dating back to the 16^{th}-17^{th} century. It is located in the outskirts of Saranda, in the village of Dhiver (Fig 1). This church is situated inside a monastery complex and it is proclaimed a monument of culture by IMK (Intitute of Monuments of Culture Albania).

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Figure 4.Photographic Information for the church

Existing conditions of the building were investigated by in-situ survey. The church is composed of naos and narthex. It is a three-apse single-nave church with inner dimensions 7.60 x 2.70 m (excluding the side apses). The naos is divided into three parts by two pairs of piers on the northern and southern walls.

The central part has a square plan and is covered by a dome on a high drum. While, the side parts are covered by barrel-vaults. The drum leans on the vaults of side parts and on the conchs of the side apses. The sanctuary area is composed of the wide apse and the sections of prothesis (northern) and diakonikon (southern).

At a later time, the narthex was constructed on the west side of the naos. The expansion joint and different construction technique show that these two have been constructed in different times. Meanwhile, the old entrance to the naos has been closed up by masonry. Narthex has a rectangular shape and is connected to the naos through an arch. It is covered by a gable roof, which is lower than the church's roof.

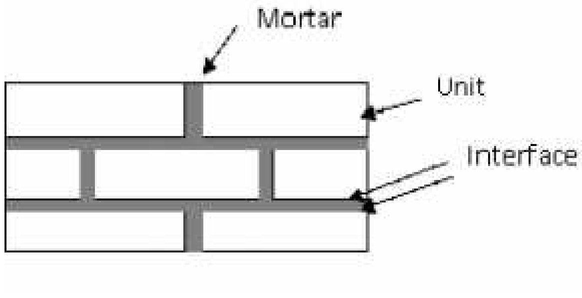
Several types of weaving are present throughout the wall of the church. They are different both for material (stone, brick and etc.) and shape (*opus mixtum, opus quadratum*, etc.). This variegate picture reflects the modifications endured over centuries by the church. However, despite the differences on the masonry texture, the construction is mostly made of irregular sandstone masonry (local stone) with thick lime mortar joints, which is used in general in this type of churches.

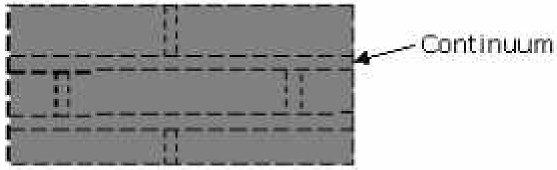
2 NUMERICAL ANALYSIS

From a structural point of view, historical masonry buildings are generally capable of carrying vertical loads in a safe and stable mode, whereas they are rather sensitive to horizontal loads. The seismic sensitivity of this type of structures is due to the particular arrangement of the structural elements and the mechanical properties of the masonry material [4].

Earthquake analysis of historical masonry buildings, particularly churches and mosques, is a rather difficult task due to: the difficulty in numerical modeling of the nonlinear behavior of masonry material, with almost no tensile strength; the incomplete experimental characterization of the mechanical properties of the masonry structural elements; and the complexity of the geometrical configuration. Refined mechanical models, which can accurately predict the response of masonry material and elements, have been proposed in the literature [3, 5, 7, 11, 12]. These kinds of models adopt different strategies to take into account the nonlinear characteristics of response quantities. However, application of these strategies is really difficult to 3D analysis of complex structural systems. On the other hand a linear elastic and dynamic analysis of the 3D structural complex provides valuable information on the global behavior and on the interaction among the single elementary parts, which constitute the structure.

For the convenient constitutive description of anisotropic behavior of masonry materials, there exist two fundamental approximations: the “Micro modeling” and the “Macro modeling” [15]. Micro and macro models for historical structures exist due to various accuracy level of the analysis. In the micro-modeling, the masonry material is taken as a discontinuous assembly of blocks connected to each other by joints. The blocks and the mortar joints are modeled separately (Fig 2a). This model is mostly preferred when a single structural element analysis is needed to be performed. On the other hand, the macro modeling approach analyses the masonry material without separating units and joints and by formulating a fictitious homogeneous and continuous material equivalent to the actual discrete one (Fig 2b). Macro modeling is better in case of necessity compromising between efficiency and accuracy and it is used when the building has solid walls with large dimensions [10].





a) Micro-modeling b) Macro-modeling

Figure 5. Modeling of masonry

The macro element approach is followed in this paper. Values concerning the physical values of masonry material have been established on statistical analysis of test data found in the literature. Thus, the church was supposed to be made of a unified material that has an elastic modulus E = 1.30E+07 kN/m^2, a unit weight γ = 22 kN/m^3 and Poison's ratio υ = 1/6. These values were determined by literature survey and by comparing the properties with similar type structures from previous studies. The three-dimensional analysis model is developed by using SAP2000 structural analysis software. Shell elements are used for preparing the analysis model. Totally, 1384 shell elements were used for the analysis model (Fig 3). It is vital to use realistic number of finite elements to gain response of the structure having acceptable level of accuracy. Using more than required number of elements might give complex results to be extracted. On the other hand, insufficient number of the elements is not capable of capturing the global behavior of the building with efficient level of accuracy. Various minor simplifications have been made to avoid the geometrical complexity of the studied structure and the number of the finite elements is kept at a minimum level as possible. However, it is elaborated for the response of the structure with a reasonable accuracy.

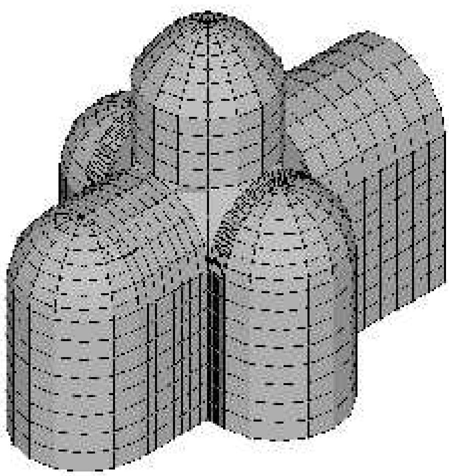
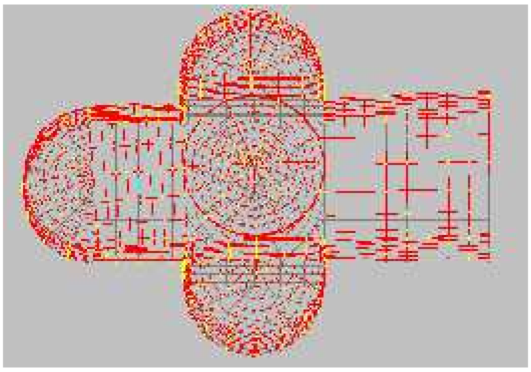


Figure 6. Structural analysis model

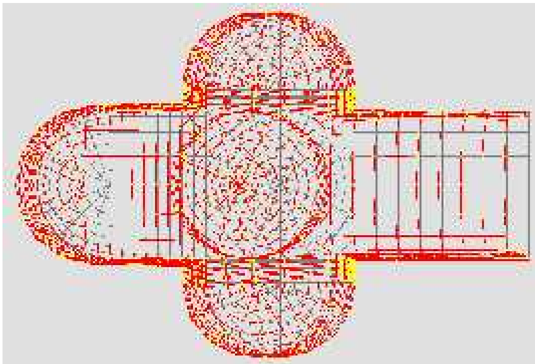
Gravity loading

Free vibration, self-weight and spectral analyses have been carried out in order to determine the structural response and the stress variations of the case study building. Analyses are performed under the assumptions of linearly elastic material as it has been done in masonry structures in order to obtain the entire global behavior.

Free vibration analysis is performed and the natural periods of the church are obtained. The first two mode shapes of the building occur in the two orthogonal directions [Fig 4]. First and second natural periods are not close, which shows the participating mass of the first two modes and the structural rigidity of the two directions are not equal to each other.



a) Deformed shape – Period 1 – 0.10206



b) Deformed shape – Period 2 – 0.06012

Figure 7. Mode shapes; first mode shape, b) second mode shape

Variation of the vertical normal stress due to the self-weight is shown in Fig 5. As expected, vertical compressive stress increases downwards and it reaches about 0.20 N/mm^2 at the lowest level. As seen in the figure, stress concentrations occur around the locations where pendentives merge with the drum and the tensile stresses at the edges of these locations increases up to 0.25 N/mm^2. Small tensile stresses occur at the top levels of the barrel vaults due to the out-of-plane loads originating from the dome and drum. The compressive stresses along the meridian direction at the bottom level of the main drum are obtained about 0.10 N/mm^2.

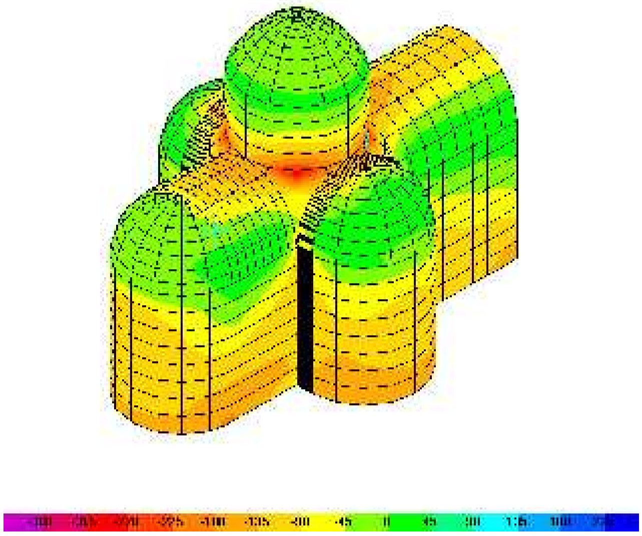


Figure 8. Self-weight analysis – Vertical normal stresses (N/mm^2)

Earthquake loading

Regarding the effects on buildings, seismic actions can be defined as the movement of the foundation of the ground under structure. Horizontal components of the ground acceleration are assumed to be the most destructive ones for the overall structural behavior; therefore the seismic effects are related to the structural resistance to horizontal action. In Albania, during the past centuries, the region has experienced several destructive earthquakes and it is one of the places in this Balkans where the historical strong earthquake events were documented [1].

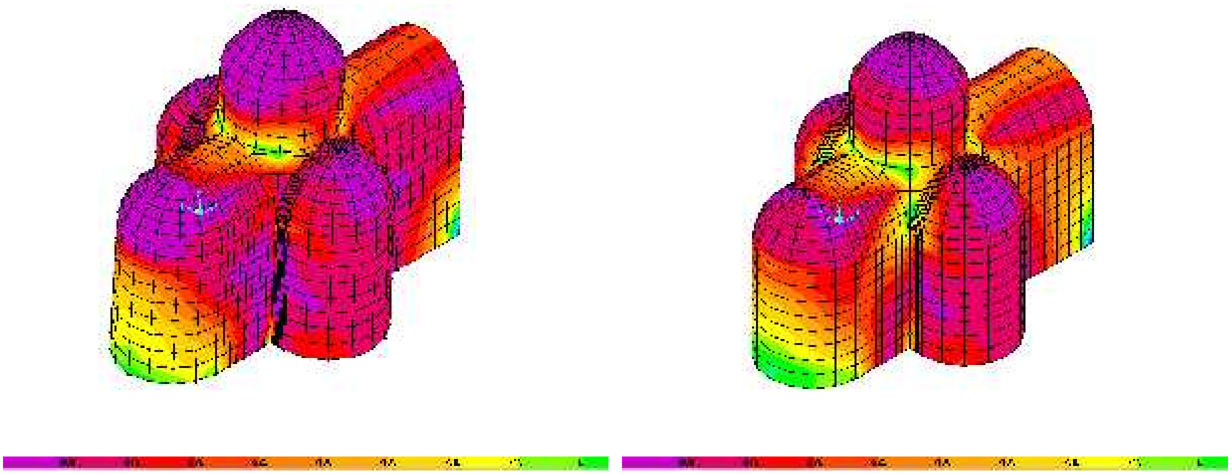
A geotechnical site investigation has been carried out to specify the type of soil characteristics underlying the cased study church. After completed drillings, sample soils are tested in laboratory for physical-mechanical properties. According to the test results, shear velocity has a range of 950 – 1150 m/s. Spectral earthquake analysis is carried out by using the spectra defined in UBC-97 [17]. The response spectrum in UBC-97 is related to the site specific values of C_a, C_v which is given in Table 2. This corresponds to soil type B in UBC-97.

Table 2. The values of C_a, C_v according to the soil type (UBC-97)

Soil type	Soil profile name/ Generic description	Shear wave velocity (m/sec)	C_a	C_v
S_A	Hard rock	> 1500	0.32	0.32
S_B	Rock	760 – 1500	0.40	0.40

S_C	Very dense soil and soft rock	360 – 760	0.40	0.56
S_D	Stiff soil profile	180 – 360	0.44	0.64
S_E	Soft soil profile	< 180	0.36	0.96

Albanian design code provides PGA distribution map for minimum 10% probability of being exceeded in life time of 50 years which corresponds to return periods of 475 years. This PGA distribution map is used for the design of engineering structures. However, for the historical buildings a longer life time up to 200 years should be considered. Since the present building has a historical value, the spectra is increased by the factor of which 1.5 which approximately corresponds to a maximum probable earthquake having an exceeding probability of 2% in 50 years and a return period of 2475 years. For comparison the numerical calculations have been carried out for the two spectra, which correspond to the design and maximum earthquake. Comparison of the two spectrum analysis is given in Fig 6. As it is expected, the vertical normal stress has reached up to 50%, when maximum of the maximum earthquake is considered.



a) b)

Figure 6. Comparison of the vertical normal stresses for the N- S earthquake directions (N/mm^2), a) design earthquake,, b) maximum earthquake

3 CONCLUSION

Monumental structures are one of the most crucial parts of the cultural heritage that reflect the history of mankind. Such monumental buildings are a sound reminder of the glories of the human history in a world which is diminishing in terms of space and time. Therefore, it is very important to protect them by taking measures from structural aspect without losing time.

Typological classification of churches constructed in post-byzantine architecture has been outlined based upon the plan and spatial composition of these structures in Albania and depending upon this classification Church of the Monastery of Saint Nicholas was selected to investigate its structural performance. Existing conditions of the building were investigated by in-situ survey. Macro modeling is used in this study. It is shown that, overall structural behaviors of the building can be obtained by using a reasonable number of finite elements. The first two mode shapes of the building come into being as a result of lateral displacements and occur in two orthogonal directions. Historical structures are expected to sustain larger earthquake compared to the ordinary structures due to their highly cultural and aesthetic values. Therefore in the numerical analysis, the maximum earthquake spectra of the UBC-97 is employed, which is assumed to produce 1.5 times larger forces that the design earthquake spectra. Then two analysis results were compared. It is observed that stress concentrations occur around the transition elements and corners. Small tensile stresses are formed at the top wall levels. The vertical normal stresses increase up to 40-50%, when the maximum earthquake is considered instead of design earthquake. Under the self weight and the earthquake loading, stress concentrations occur at the corners and pendentives. The maximum stress varies around 0.7 N/mm^2 in the structure both in tension and in compression. Especially, maximum tensile stress might cause cracks for this type of masonry structures. However, it is supposed that there are wooden lintels and other connection components within the structural walls that are used to resist the tensile stresses and to provide the structural integrity for this type of historical structures. It is the most probably why there is no damage in these parts, although tensile stresses are expected.

Today's advanced computing utilities provide new horizons for the definition of monumental structures. Even though the obtained results cannot be considered as fully realistic, deformed shape, graphical stresses and force distributions reveal considerably true response of the case study building. With this study, we both learn the values that we possess and the existing conditions of these buildings are documented with one case study. Preserving and strengthening programs could be done on the basis of this documentation and conservation strategies could be developed according to them.

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