Simulation and Numerical Modelling of Heritage Stone Masonry Timber Structure in Seismic Region

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Keywords: Heritage Structures, Simulation, Numerical Modelling, Seismic Performance, Preservation.

Abstract: Numerical modelling of heritage structures is a very challenging task. The difficulties are related to the adequate computer modelling of the used construction materials and the adequate modelling of the structural elements and their connection. In the context of the above, it is necessary to specify a lot of input information and to thoroughly study the output data of the analyses. The paper presents the process of creating and analysing different numerical models for a heritage stone masonry-timber structure of an ancient church in Bulgaria. The Orthodox Church "Transfiguration of the Lord" in the city of Pomorie, Bulgaria was built in the second half of the 18th century. The church is a three-nave building with a timber roof. The combination of different construction materials – stone and wood and the specific geometry and details of the structure, impose the creation of several numerical models, especially when studying the seismic behaviour. The final conclusions for the structure and the structural elements are made using the results from different computer models. Finally, some more general recommendations for the application of the variant research in modelling in order to obtain best results are given.

1 INTRODUCTION

Modelling the performance of heritage structures is important stage for every preservation project (Partov D and Traykova, 2017., Traykova M and Chardakova T, 2017., Traykov A, 2017). Numerical modelling is able to reflect more complex, and hopefully more accurately, the behaviour of the studied structure, mainly in terms of its geometry, the behaviour of various structural components and their interaction. That stage is part of a bigger plan for investigation and rehabilitation of structures with historical value. Methods and approaches for dealing with such tasks are discussed in (Roca P, 2020., Nowogonska B, 2020., Coïsson E, Ferretti D, Pagliari F, 2020 and Panto B, et al., 2020). The knowledge of a significant number of designers is required in order to create accurate and convincing computer models of intricate historic buildings. (Traykova M, 2019). It is probably best to start with the simplest realistic model and then, if necessary, develop a model that reflects more structural features and complexity (Traykova M and Traykov A, 2021., Maeda T, et. Al., 2020) regardless the type and the complexity of the analysis. In order to prolong the life of the structures and preserve them for the future, it is necessary to develop an appropriate structural model so that the behavior of the structure can be evaluated, its vulnerable areas can be located, and risks can be reduced. In light of the aforementioned, it is essential to detail a significant amount of the supplied information. (Traykova M and Ivanova B, 2021 and Traykova M and Traykov A, 2021) and to thoroughly study the output data of the analyses (Partov D, Ivanchev I and Traykova M, 2019).

The research that is presented in the paper details the process of consecutive iterations that were carried out with the intention of providing the most accurate and detailed information for the behavior of the structure as well as the most effective measures that can be taken to preserve the building Partov D, Ivanchev I and Traykova M, 2019).

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Traykova, M., Traykov, A. and Shouaib, R.
Simulation and Numerical Modelling of Heritage Stone Masonry Timber Structure in Seismic Region.
DOI: 10.5220/0012107400003680
In *Proceedings of the 4th International Conference on Advanced Engineering and Technology (ICATECH 2023)*, pages 324-330
ISBN: 978-989-758-663-7; ISSN: 2975-948X

2 GENERAL DESCRIPTION OF THE BUILDING

The Orthodox Church "Transfiguration of the Lord" in the city of Pomorie (Figure 1), Bulgaria was built in the second half of the 18th century. The church is a three-nave building with a timber roof. According to preserved historical sources, the church was built on top of an early Christian basilica in 1763-64 and consecrated in 1765. It is also the oldest building in the entire city of Pomorie. It houses valuable examples of iconographic art from the 15th-19th centuries, with the oldest icon being from the end of the 15th century, the beginning of the 16th century. The plan of the church is a rectangle with dimensions of 24.60 m by 12.10 m (Figure 2). The approximate thickness of the stone masonry walls in the main part of the building is about 1m, but it varies within ±5 cm.

Figure 1: Main entrance of the church.

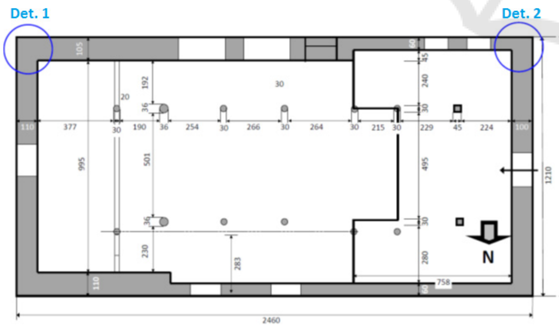


Figure 2: Plan of the church.

The structure of the church is massive, constructed from an insignificant amount of worked stones used for the corners of the building, as well as from roughly cut stones with a very heterogeneous petrographic composition, arranged with wide lime joints. The petrographic origin of the rocks used for stone blocks differs significantly, predominating the specimens of sedimentary rocks, but metamorphic rocks, mainly marble, have also been found. Stone blocks of sandstones were found as individual specimens. A significant part of the stone blocks has a wet surface with a depth of 10-15 mm from the surface, and some are even cracked as a result of loads or operational impacts. The connection is made by means of lime mortar, and the joints during the last renovation works of the church were locally surface treated with cement mortar.

In the longitudinal direction of the stone walls, internal connections are made with solid timber elements (Figure 3).

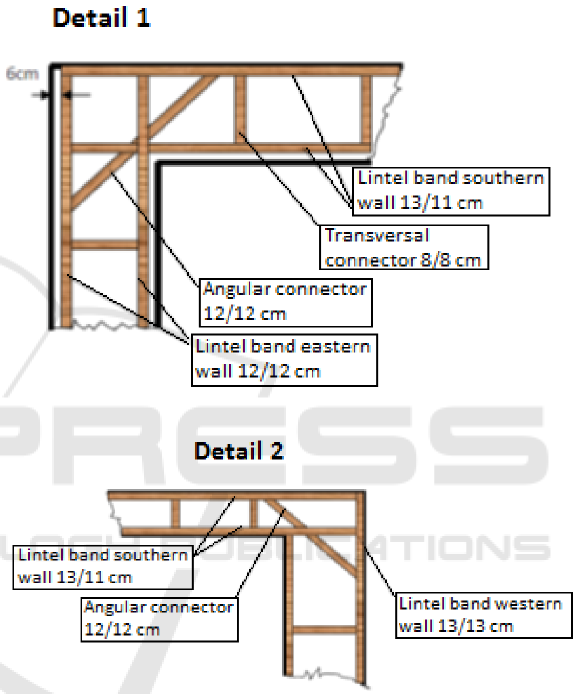


Figure 3: Timber elements used for masonry structure.

3 NUMERICAL MODELLING

There is a large volume of literature devoted to computer modelling of structures. While some of the books have a more general nature (Feng Fu, 2015) and a significant volume, a significant part of the publications present specific methods related to the numerical modelling of buildings and facilities with historical and cultural value (Panto B, 2020., López López D, 2020., Hassanieh A, Gharib M, King M, 2020), and some of them present a methodology related to the analysis of specific buildings or bridges (Gobbin F, et. Al., 2009 and Mentese V, Celik O, 2020). Comprehensive study and practical approach for numerical analysis and assessment of masonry structures is presented in (Iannuzzo A, et al., 2020). For the purpose of the preservation project considered in the present paper, 3D computer computational models of the church were created with the software SAP2000 (CSI software). The geometry of the structure, the characteristics of the used materials, as well as the geotechnical data for the ground base, defined during the "on site" investigation, were taken into account in the models.

The following construction materials characteristics are defined in the computer models for modelling the structure (all characteristics are defined "in situ" or on specimens in the Laboratory of University of Architecture, Civil Engineering and Geodesy, Sofia, Bulgaria):

- Timber – Modulus of elasticity

$$E = 3000 \text{ MPa} \quad (1)$$

Characteristic compressive strength:

$$f_{c,90,k} = 7{,}25 \text{ MPa} \quad (2)$$

Characteristic tensile strength:

$$f_{t,0,k} = 14{,}53 \text{ MPa} \quad (3)$$

The weight per unit volume is 8 kN/m^3;

- Masonry – Modulus of deformation E_k = 1626 MPa;

$$E_k = 1626 \text{ MPa} \quad (4)$$

The weight per unit volume is 18 kN/m^3.

The limited level of knowledge for the construction materials requires the reduction of the characteristics with a confidential factor

$$CF_{KL1} = 1{,}35 \quad (5)$$

according to EN 1998-3 (European Standard – part 3, 2005).

Concerning the checks for the bearing capacity and the deformations, the requirements of the standards Eurocode are followed.

3.1 Numerical Modelling of the Timber Roof (Model 1)

This model aims to provide information about the elements of the timber roof structures. According to the location of the city, the specific loading for wind and snow are considered.

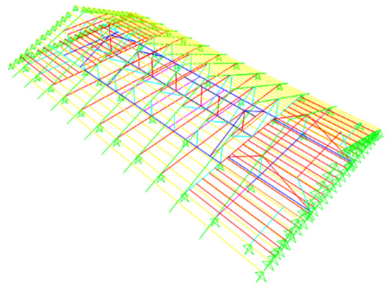
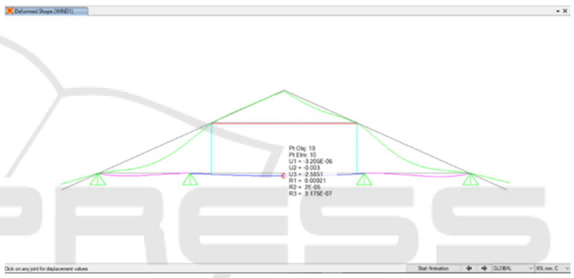
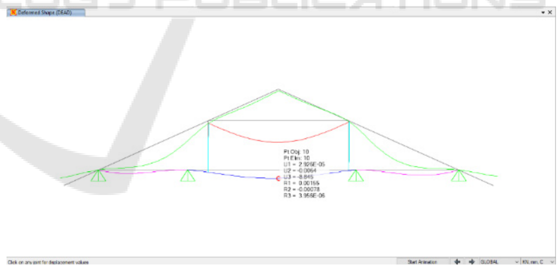


Figure 4: 3D model of the timber roof structure.

The elements of the timber roof are checked. Special attention is provided for the deformations because of many real damages in the roof found during the site investigation (Figure 5).



a)



b)

Figure 5: Deformation of the most unfavourable timber truss from: a) permanent loading; b) wind loading.

Based on the structural analysis carried out and the results obtained after the analysis, it was found that one part of the timber elements need strengthening. A special project was developed with specific details for strengthening of the roof elements. This local 3D model of the roof was very useful for the realistic assessment of the condition of the analyzed structure. The reactions of the roof subsequently are applied in one of the next models.

3.2 Numerical Modelling of the Building Structure (Model 2)

Modelling and linear static analysis of the structure is carried out according to Eurocode (European Standard – part 1-3, 2005). Two 3D computational models have been developed using the finite element method in the SAP2000 software product environment. All elements of the structure, including the roof, are presented in the first model (Variant 1, Figure 6). That model is analyzed for load combinations: seismic, in order to obtain the maximum horizontal displacements, and also the main (fundamental) load combination to obtain internal forces from ultimate limit states. Due to the fact that the timber roof structure is "softer" compared to the stone masonry structure and in order to specify the real behavior of the structure, a second model was created (Variant 2, Figure 7) where the timber roof structure was replaced with the loads from its support reactions. The following types of finite elements (FE) were used in the models: for the planar elements – two-dimensional shell finite elements, elements with smaller cross-sections and less linear bending stiffness are modeled with one-dimensional frame finite elements. The elements at the edge are modified in a way to reflect the performance of the supporting structure as accurately as possible.

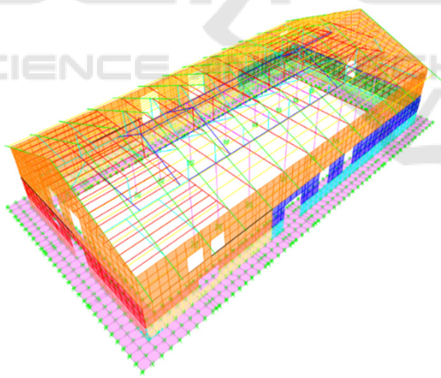


Figure 6: Variant 1 3D model of the masonry structure and the timber roof.

The presence of cracks in the walls was accounted for in the computer model by forming a critical zone, with a height of about 1/6 of the height of the wall, in which the elastic stiffness is reduced by 50%.

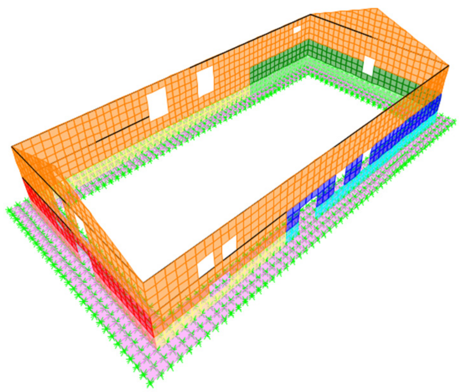


Figure 7: Variant 2 3D model of the masonry structure without the timber roof.

The seismic analysis of the building is carried out by means of the response spectrum method. The first natural period of the structure is T1=0,1166 s, the activated masses are more than 90% in horizontal and vertical directions. Maximum displacement at the top of the wall under seismic loading is 15 mm.

According to the seismic map of Bulgaria (European Standard – part 1, 2004) ground acceleration

$$a_{g,R} = 0.11g \qquad (6)$$

$a_{g,R} = 0.11g$ is adopted. The soil is category D

According to (European Standard – part 1, 2004) and after the special geotechnical investigation on site. A very weak backfilling with low bearing capacity was found as a soil layer under the building. According to the geotechnical report a value of ks is 5000kN/m^3 for the soil area stiffness is adopted in the computer model. The importance factor is

$$\gamma_I = 1,2 \qquad (7)$$

as the church is a specially protected heritage building. A behaviour factor

$$q = 1,5 \qquad (8)$$

It is adopted according to (European Standard – part 1, 2004) as the structure is one of a limited ductility. Horizontal and vertical design response spectrum according to (European Standard – part 1, 2004) is used for the calculation of the accelerations.

A comparison between the results of the two variants are made for the different internal forces: F11, F22, M22, V23 (Figures 8, 9).

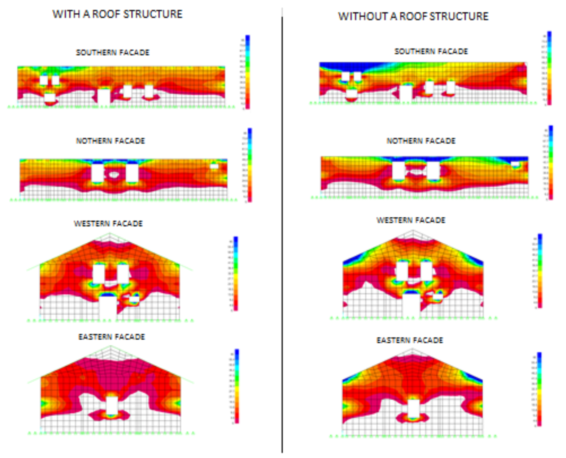


Figure 8: F11 – Comparison between Variant 1 and Variant 2.

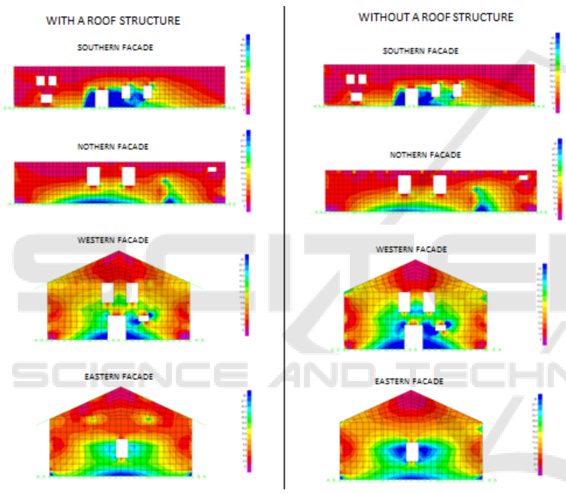


Figure 9: M22 – Comparison between Variant 1 and Variant 2.

Due to the predominant effect of vertical loads, the stresses in the walls are mainly compressive. The analysis of the two combinations (fundamental and seismic) shows the occurrence of local tensile forces with minimum values in the areas around the openings. Local tension also appears in the areas of the triangular walls on the east and west facades at the points where the timber structure is supported. This is found in both combinations, as for the seismic one, the values are slightly higher compared to the fundamental combination.

The main conclusion that can be drawn from the actual comparison of the two variants of Model 2 is that the addition of the roof structure leads to some redistribution of forces in limited-sized and localized areas of the walls, but the forces do not change as values. As expected, the stress concentration zones are local and concentrated around the openings. In connection with the results obtained from the numerical analyses of the models, it can be assumed that in practice the zones in the walls, in which there are locally significant stresses, are present in very small areas. Given the status of the church and the need for preservation of its authentic vision, it is appropriate to recommend taking measures to repair the cracks in the walls and improve the spatial performance of the masonry structure by improving the connection between the walls/facade walls and the connection between the roof structure and the walls.

4 CONCLUSIONS

The numerical modelling provided for the preservation project of the church "Transfiguration of the Lord" in the city of Pomorie, Bulgaria led to the following particular as well as more general conclusions and recommendations:

1. The analysis of the numerical results obtained as a result of the simulation of the behaviour of the building shows that the structure is able to resist the provided by Eurocode vertical and horizontal loads acting on it.
2. Usually creating one numerical model is not sufficient to cover the specific features of the structure and its elements and to reflect all details and complexity of the structure. The two numerical models discussed in the paper provide better information about the structural behaviour and the specifics of the contribution of the different elements of the building to its overall response to actions.
3. Based on the numerical models provided in the research, it was possible to prepare a special preservation project that includes three groups of activities: 1) Rehabilitation and strengthening of the roof structure; 2) Rehabilitation and strengthening of the stone masonry structure; 3) Rehabilitation and strengthening of the foundations. There is many construction solutions reported in the scientific literature and implemented by the professionals for rehabilitation, strengthening and conservation of structures of historical value.
4. The numerical modelling of heritage structures presents increasing challenges to structural engineers – complex structural geometry, specific structural schemes, different types of existing damages, necessity to find the real characteristics of specific old construction

materials, etc. The option to analyse different models brings the opportunity to select easier the different techniques and structural solutions for each specific part of the structure. That approach allows for the optimization of the structural design and for minimizing the construction cost. Future work envisages monitoring the behaviour of the building, as well as developing computer models for the analysis of the non-linear structural behaviour based on the available data.

ACKNOWLEDGEMENTS

This work was supported by AVT Consult Ltd, Bulgaria.

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