BULETINUL INSTITUTULUI POLITEHNIC DIN IAȘI
Publicat de
Universitatea Tehnică „Gheorghe Asachi” din Iași
Tomul LX (LXIV), Fasc. 3, 2014
Secția
CONSTRUCȚII. ARHITECTURĂ

ANALYTICAL EVALUATION OF THE SEISMIC VULNERABILITY FOR MASONRY CHURCHES USING THE FINITE ELEMENT METHOD

BY

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Received: June 19, 2014
Accepted for publication: July 14, 2014

Abstract. A large part of the built cultural heritage is affected by structural damages which may lead to infrigements of the quality essential requierments of the buildings. Structural analysis contributes to the safety assessment and design of the necessary interventions, therefore accurate results are needed in order to avoid defective rehabilitation solutions. In this paper, three old masonry churches are presented. For each of the latter, the approach consisted in geometrical surveying of the buildings, laboratory testing of masonry samples extracted from the site aiming to determine its mechanical properties, followed by linear static analysis of the structures using a software based on the finite element method (FEM). The effective shear force for each masonry wall was calculated and, afterwards, it has been compared with the capable one, previously analytically evaluated based on the provisions of the active seismic norms. In this way, the seismic safety level of the building has been evaluated.

Also, this paper presents some aspects regarding the seismic protection level of this type of buildings, characterized by complex construction typologies.

The results of the case studies prove to be usefull tools in classifying the old masonry structures with respect to their seismic safety level, in order to fully comprehend and investigate the seismic vulnerability of the existing built cultural heritage.

Key words: cultural heritage buildings, old masonry churches, FEM analysis, seismic safety level.

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1. Introduction

Old masonry structures with structural integrity under gravitational loads may demonstrate a very low capacity against earthquake, even of low intensity, due to the combination of heavy weight and high stiffness along with the lower tensile strength. The assessment of the seismic vulnerability of an ancient masonry building is a challenging task, because of several uncertainties affecting the geometrical and the mechanical characteristics of the structural elements (1).

An adequate methodology to assess the seismic vulnerability of masonry historical churches consists of the following main steps (2): research, compilation and analysis of relevant historical data; installation of static and dynamic monitoring systems; experimental tests for mechanical characterization of materials and/or structural elements; dynamic identification of the structure; numerical modelling and model calibration against existing experimental results, as a tool to simulate the structural behaviour; linear and non-linear static analyses for different seismic hazard levels; identification of structural vulnerabilities, collapse modes and safety evaluation; recommendations to minimize the seismic vulnerability of the construction, including possible intervention solutions for its conservation/rehabilitation or strengthening.

While for new masonry structures it is possible to have adequate tools toward the correct evaluation of their structural behaviour, as the analysis turns to “historical” constructions such task becomes harder and harder. The needs of preservation of the historical, cultural and architectural essence of the building in many cases contrast with the needs of providing the “adequate” necessary capacity to its structure, in order to withstand the design seismic loads (3).

1.1. Evaluation Methodology of the Seismic Safety Ratio

Analytical evaluation by calculation according to the P100/3-2008 regulation (4) is a quantitative method which checks whether existing buildings, damaged or not, meet the limit state considered in the associated seismic action computations.

For each wall of the analyzed structures, the minimum capable shear force is analytically determined for a horizontal section at the base of the building. By comparing the bearing capacities with the shear forces resulted from the linear static analysis, using FEM, the safety factors for each masonry wall can be obtained.

The ratio of the structural capacity and seismic requirement, expressed in terms of strength, is the factor R_3 and represents the structural seismic safety level. For the analyzed buildings, R_3 coefficient was calculated for each masonry wall on the two main directions, longitudinal and transversal.

The relation for the R_3 coefficient computation is the following:

$$R_3 = \frac{\sum_{jd} V_{fd} + \sum_{kf} V_{ff}}{F_b}, \tag{1}$$

where: $\sum_{jd} V_{fd}$ is the sum of the bearing capacities of wall with ductile fracturing; $\sum_{kf} V_{ff}$ – the sum of the bearing capacities of wall with fragile fracturing.

The bearing capacities of the walls are introduced with the following values:

$$V_{fd,i}(V_{ff,i}) = 0 \text{ for } R_{3i} < 0.5, \tag{2}$$

$$V_{fd,i}(V_{ff,i}) < 1.5F_{b,i}. \tag{3}$$

Based on the analytically determined safety factor, the seismic risk classes are presented in Table 1.

Table 1

R_3 Values Associated with Seismic Risk Classes (P100-3/2008, 8.2.5 Tabel 7.3)

Seismic risk classes			
I	II	III	IV
R_3 values, [%]			
<35	35…65	66…95	96…100

2. Study Cases

The Bărboi Church in Iaşi (Fig. 1), dates from 1,841…1,843, keeping intact the original shape of a Greek cross plan, with small semicircular apses and prismatic pilasters. The church has a length of 28.80 m and 18.55 m wide with walls made of stone blocks alternating with rows of brick tied with a 5cm thick mortar layer. The height at the cornice of the church walls is 12.16 m and 18.95 m at the large central tower. The church consists of a rectangular room, separated longitudinally by two rows of four circular columns. In the transversal direction the lateral columns of the two marginal rows separates the nave from the narthex and altar. To the west, the nave is extended with a porch. On the columns capitals and walls pilasters a network of arches is placed. The vaults and domes are made of brick masonry with a 25 cm thickness (5).

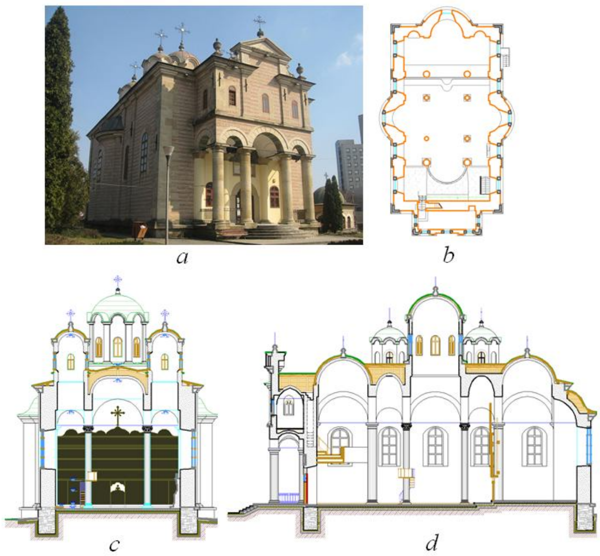

Fig. 1 – Bărboi Church: *a* – main facade; *b* – the plan of the walls; *c* – transversal section; *d* – longitudinal section (5).

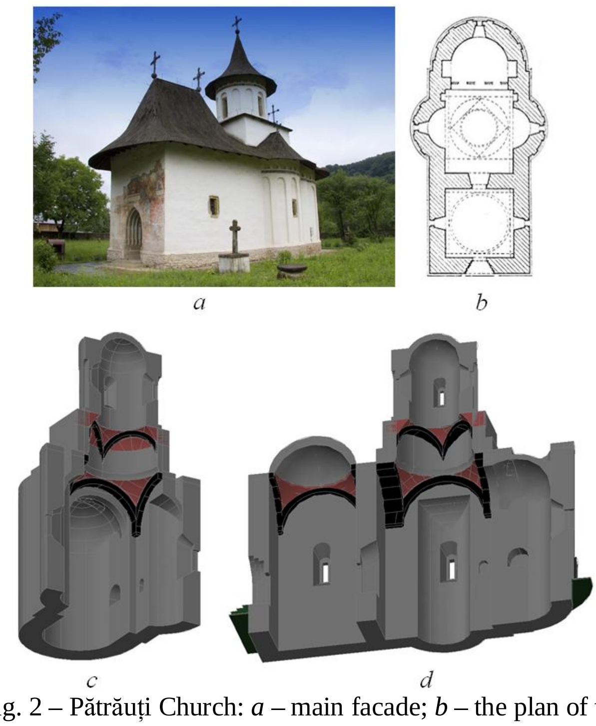

Fig. 2 – Pătrăuți Church: *a* – main facade; *b* – the plan of the walls; *c* – transversal section; *d* – longitudinal section.

The Church of the Holy Cross was a built in 1487 by Prince Stephen the Great in Patrăuți village in Suceava county. It is a construction on triconical plan with the tower supported by for rotated arches above the nave and a specific orthodox subdivision of the space in narthex, nave and altar. The walls have a thickness of about 1 m and are made of rough stone layers wich alternates with rows of bricks. The lateral apses are semicircular on the interior and polygonal at the exterior (Fig.2).

The “Three Hierarchs” Chapel (Fig. 3) has a length of 17.76 m and a width of 5.60 m at the porch extended to 8,54m at the aisles. The church was built between 1902 and 1911 with walls, arches and vaults made of brick masonry and lime mortar. It has classic plan for Moldovian churches, in a cross form, with out-of-plan side aisles and altar, all with a polygonal shape at the exterior and circular shape at the interior. The space partition is marked externally by widening the width of the plan, from the porch to the nave and aisles (6).

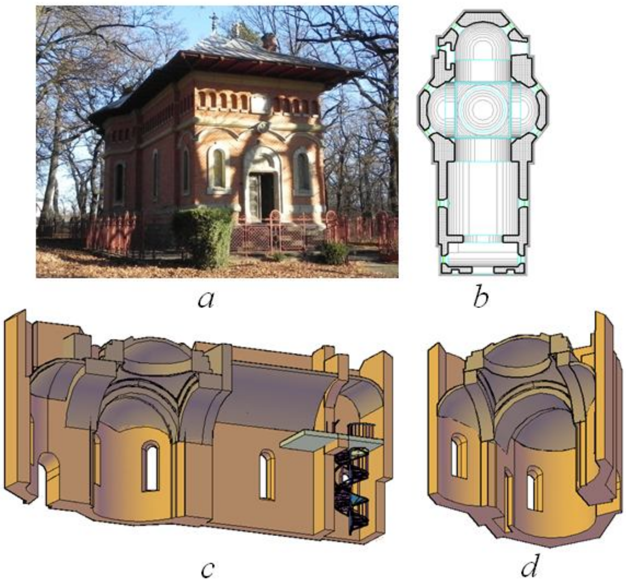

Fig. 3 – The “Three Hierarchs” Chapel: *a* – main facade; *b* – the plan of the walls; *c* – longitudinal section; *d* – transversal section.

3. Numerical Analysis

The mechanical characteristics of the materials were determined by laboratory tests on samples taken from the analyzed structures (Fig. 4). If the Three Hierarchs Chapel case bricks taken from the church attic were tested in compression and bending.

From Bărboi and Pătrăuți Churches walls samples of stone and mortar were extracted by coring and tested in laboratory. Mechanical characteristics of the materials considered in the calculation are presented in Table 2.

Fig. 4 – Experimental tests for mechanical characterization of the materials.

For the calculation in the linear elastic range, with consideration of factor *q* (reduced spectrum), the design strengths of masonry are taken as follows:

Table 2
Materials mechanical proprietes

Materials mechanical proprietes	Bărboi Church	Pătrăuți Church	Sf.Trei Ierarhi Chapel
Unit compressive strength, [N/mm^2]	f_b = 16.35	f_b = 14.15	f_b = 3.5
Mortar compressive strength, [N/mm^2]	f_m = 5.25	f_m = 3.60	f_m = 1
Confidance factor	CF = 1.2	CF = 1.2	CF = 1.2
Material safety factor	γ_M = 3	γ_M = 3	γ_M = 3
Masonry compressive strength, [N/mm^2]	f_d = 2.10	f_d = 1.69	f_d = 0.52
Masonry tensile strength, [N/mm^2]	f_{td} = 0.084	f_{td} = 0.068	f_{td} = 0.021
Masonry longitudinal elasticity modulus, [N/mm^2]	E_z = 5,814	E_z = 4,692	E_z = 1,202

The structural analysis of the churches was made by subjecting the finite element models to three types of actions: dead load, live loads and seismic loads. The actions were defined in accordance with Romanian standards, in agreement with Eurocode 8. Table 3 presents the load cases defined by the code.

Table 3
Load Cases

The fundamental loading cases	$1.35\sum_{j=1} G_{k,j} + 1.5Q_{k,i} + \sum_{i>1} 1.5\Psi_{Q,i}Q_{k,i}$
The special loading cases	$\sum_{j=1} G_{k,j} + \gamma_I A_{Ek} + \sum_{i>1} \Psi_{2,i}Q_{k,i}$

Where: $G_{k,\,j}$ is the dead load; $Q_{k,i}$ – the live load; $Q_{k,\,j}$ – the predominant live load; $\Psi_{0,1}$ – the live load factor equal to 0.7; A_{Ek} – the earthquake action for a recurrence interval of 100 years, P100 - 2006; $\Psi_{2,i}$ – the live load coefficient equal to 0.4; γ_I – the coefficient of importance equal to 1.20 for importance class 2.

The seismic actions have been introduced in the program in a response spectrum analysis using the design accelerations spectra (Fig. 5) according to the national code P100/2006 (8).

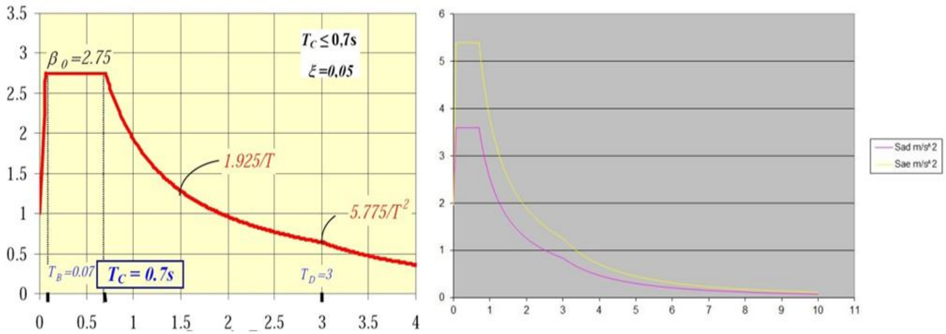

Fig. 5 – Elastic and design accelerations spectra.

Because of the complex geometry of this kind of construction and the difficulty in nonlinear modeling of masonry, earthquake analysis on historical masonry churches is a difficult task. Linear elastic and dynamic analysis of the construction 3-D models offers essential information regarding the global behavior and the interaction between structural elements.

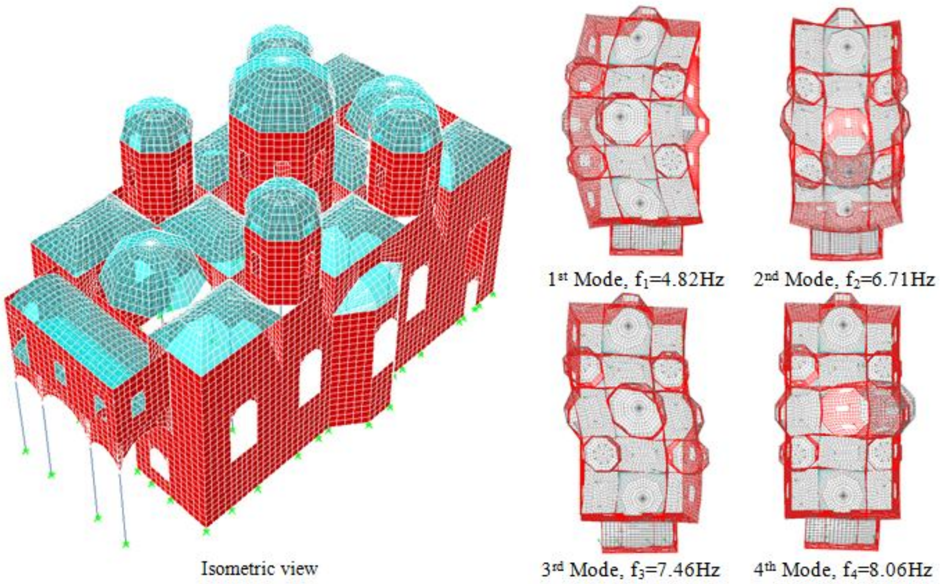

Fig. 6 – FEM analysis of Bărboi Church.

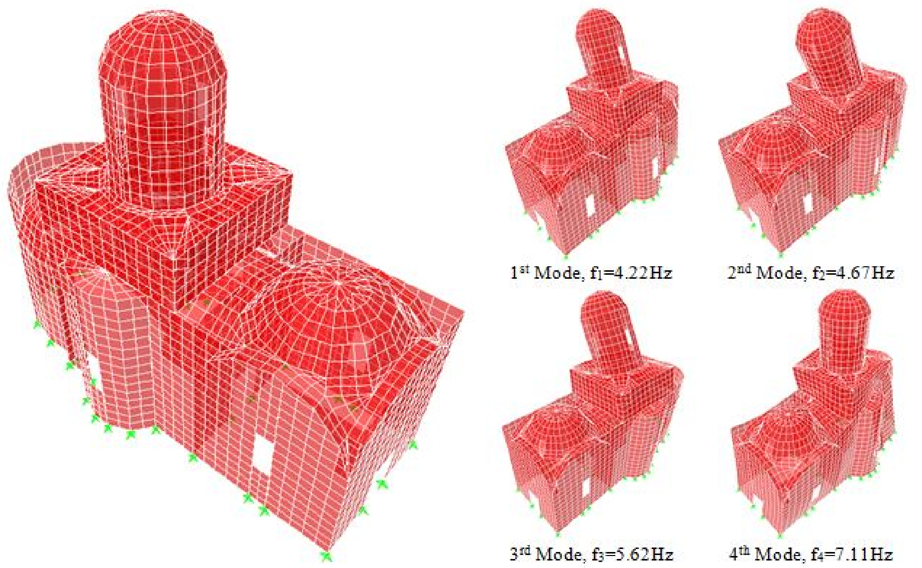

Fig. 7 – FEM analysis of Patrauti Church.

In this paper, because the analyzed churches have solid walls with large dimensions and the necessity compromising between efficiency and accuracy, the macro modeling strategy was followed. This approach is simplified by means of abolishing the difficulty of distinctive characteristics of unit, mortar and unit-mortar interface, and introducing the concept of homogeneous anisotropic continuum into the masonry as a whole (Lourenco, 1996).

The analysis models were developed by using Etabs V9.7.4. software (Figs. 6,…,8).

A simplified approach, based on P100/3-2008 Romanian code (Betti & Galano, 2012), was used to manually compute the load bearing capacity. Three failure mechanisms of masonry walls are taken into account: rocking, sliding shear and diagonal shear cracking (Fig. 9).

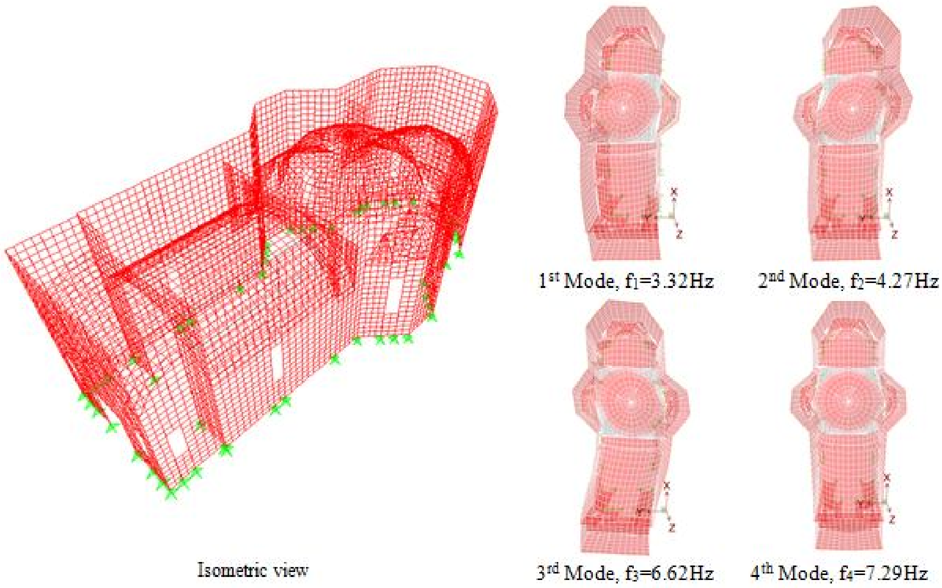

Fig. 8 – FEM analysis the “Three Hierarchs” Chapel.

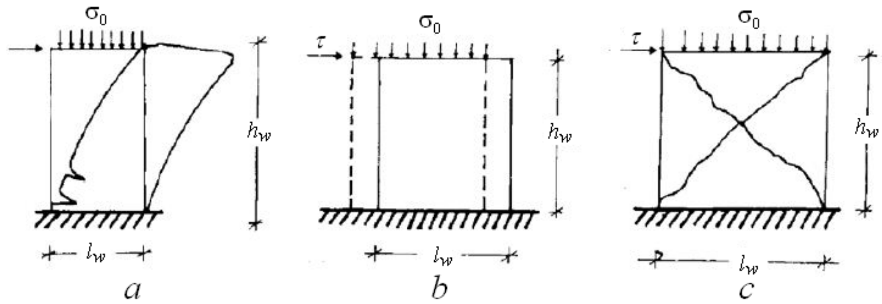

Fig. 9 – Failure mechanism of a masonry wall: *a* – rocking, *b* – sliding shear, *c* – diagonal shear cracking.

Rocking failure occurs when the moment at any of the end sections of the effective pier length attains the ultimate moment. According to P100/3-2008 ultimate moment equivalent shear force can be computed with the first equation from Table 4.

The second criteria refers to sliding shear failure based on a Mohr Coulomb formulation and considers a simplified distribution of compression stress. The shear strength is given by the second equation from Table 4. The diagonal shear cracking strength for in plane actions is given by the third equation.

Table 4
Load bearing capacity for a masonry wall (P100/3-2008)

Failure mechanism	Equation
Rocking	$V_{f1} = \frac{N_d}{c_p \lambda_p} \nu_d (1 - 1.15\nu_d)$
Sliding shear	$V_{f21} = f_{vd} D' t$
Diagonal shear cracking	$V_{f22} = \frac{t l_w f_{td}}{b} \sqrt{1 + \frac{\sigma_0}{f_{td}}}$

Where: N_d is the walls axial force; λ_p – masonry wall form coefficient; ν_d – normalized vertical stress; f_{vd} – compressive design stress; D' – length of the compression zone; f_{td} – tensile design strength; b – coefficient with values between 1 and 1.5.

Following the computation scheme above analyzed, in Table 5 is presented, as an example, the calculation of the safety factor for a masonry wall of the Bărboi Church.

Table 5
Safety Factor Computation for a Wall (R_3)

Wall *t*	t m	l_w m	N_d kN	V_d kN	V_{f1} kN	V_{f21} kN	V_{f22} kN	$V_{f\min}$ kN	R_{3i}
L1A	1.50	1.45	528.37	203.48	52.18	82.89	243.07	52.18	**0.256**

For each wall of the analyzed structures, the minimum capable shear force is analytically determined for a horizontal section at the base of the building. By comparing the bearing capacities with the shear forces resulted from the linear static analysis, using FEM, the safety factors for each masonry wall can be obtained.

The ratio of the structural capacity and seismic requirement, expressed in terms of strength, is the factor R_3 and represents the structural seismic safety level. For the analyzed buildings, R_3 coefficient was calculated for each masonry wall on the two main directions, longitudinal and transversal.

The relation for the R_3 coefficient computation is the following:

Using relations (1), (2) and (3) and comparing the global bearing capacity of the structure with the seismic demand, the R_3 coefficients for both transversal and longitudinal direction, was obtained for the analyzed study cases (Table 6).

Table 6

Structures Safety Factors (R_3)

Church	Safety factors		
	Longitudinal direction	Transversal direction	Global
Bărboi Church	0.559	0.317	**0.438**
Pătrăuți Church	0.311	0.281	**0.296**
Three Hierarchs Church	0.350	0.274	**0.312**

4. Conclusions

Based on the analytically determined safety factors, the seismic risk classes of the three churches are presented in Fig. 10.

The assigning of the first and second class of seismic risk to the churches is justified by the fact that, obviously, a series of damages from previous earthquakes are hidden from subsequent repairs. Moreover, the experience of such works shown that most damages are hidden under various layers of repair and the real amplitude of the existing damages of the existing structure appears during the rehabilitation work.

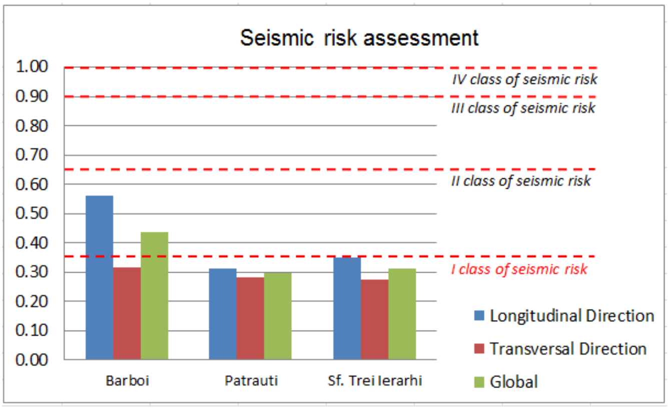

Fig. 10 – FEM analysis of Sfinții Trei Ierarhi Chapel.

Also, the characterization of the behavior of this types of constructions subjected to future seismic actions depends on many factors, both in terms of structure characteristics and in the considered earthquake actions. Since the determination of the type of intervention and its extent is closely related to the evaluated seismic risk class, a significant role is played by the expert who is responsable in interpretation and understanding the results of these types of analyzes.

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EVALUAREA ANALITICĂ A VULNERABILITĂȚII SEISMICE ÎN CAZUL BISERICILOR DIN ZIDĂRIE UTILIZÂND METODA ELEMENTULUI FINIT

(Rezumat)

O mare parte din patrimoniului cultural construit se află în prezent într-o stare avansată de degradare structurală care poate conduce la neîndeplinirea cerințelor esențiale de calitate ale acestor tipuri de clădiri. Analiza structurală contribuie la evaluarea siguranței şi proiectarea lucrărilor de intervenții necesare, prin urmare sunt necesare rezultate precise, în scopul de a evita soluții de reabilitare nepotrivite. În această lucrare, sunt prezentate trei structuri de biserici vechi din zidărie. Pentru fiecare dintre acestea, abordarea a constat în relevarea geometrică a clădirilor, testarea în laborator a probelor extrase din structuri cu scopul de a determina proprietățile mecanice ale materialelor, urmată de analiza statică liniară a structurilor folosind un program bazat pe metoda elementului finit (FEM). Au fost calculate forțele tăietoare efective pentru fiecare perete din zidărie, după care au fost comparate cu cele capabile, analitic evaluate pe baza indicațiilor din normele în vigoare. Astfel, a fost evaluat nivelul de siguranță seismic al celor trei structuri de biserici. Rezultatele studiilor de caz se pot dovedi a fi instrumente utile în clasificarea structurilor vechi din zidărie în funcție de nivelul lor de siguranță seismică, cu scopul de a înțelege pe deplin aceste tipuri de construcții complexe şi de a analiza vulnerabilitatea seismică a patrimoniului cultural construit existent.