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BEHAVIOR OF MASONRY VAULTED STRUCTURES STRENGTHENED USING REINFORCED CONCRETE BEAMS ON TOP

BY

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Abstract. Masonry churches are particularly prone to damages and partial or global collapses when subjected to horizontal loads. Knowledge of their seismic behavior is necessary to evaluate the seismic performance of these types of buildings in order to choose the proper retrofitting strategy. This paper studies the lateral stiffness of masonry vaulted structures with a head beams system of reinforced concrete as a rehabilitation solution. After carrying out geometrical assessments of two old churches and using laboratory tests on material samples taken from the site, linear static and dynamic analysis using finite element method were conducted on three-dimensional complexes with vaulted roofs. The dynamic behavior of the two analysed masonry churches with a head beams system is summarized by displaying the modal shapes with the corresponding values of the vibration period and the modal mass distribution in transversal and longitudinal direction.

Key words: masonry; vaulted churches; head beams system; modal analysis.

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1. Introduction

Churches represent an important part of the national historical and architectural heritage, assuming a symbolic significance in the center of the social life. Their great vulnerability and damages related to architectural types and construction detailes were highlited by repeatedly seismic actions. Churches were mostly constructed using unreinforced clay brick or stone masonry, and a large number partially collapsed or were suffered extensive damage. The importance of rehabilitation and preserving this kind of buildings lies both in historical and social reasons (Sorrentino *et al*., 2013).

In historic masonry churches an often chosen solution to enclose the upper space of the naves was the vaulted roof. From ancient times to today different vaults typologies were developed. According to their geometry, which is an important parameter to determine the structural behavior, the vaults were typologically classified by Carbonara, (2004), in translation vaults (generated by the movement of a straight line along a curve) and rotations vaults (obtained by the rotation of a curve around an axis). The most common and oldest roofing structure are the masonry barrel vaults (Fig. 1), that are generated by an arch translating along an orthogonal generatrix. Semicircle, parabola and elliptic

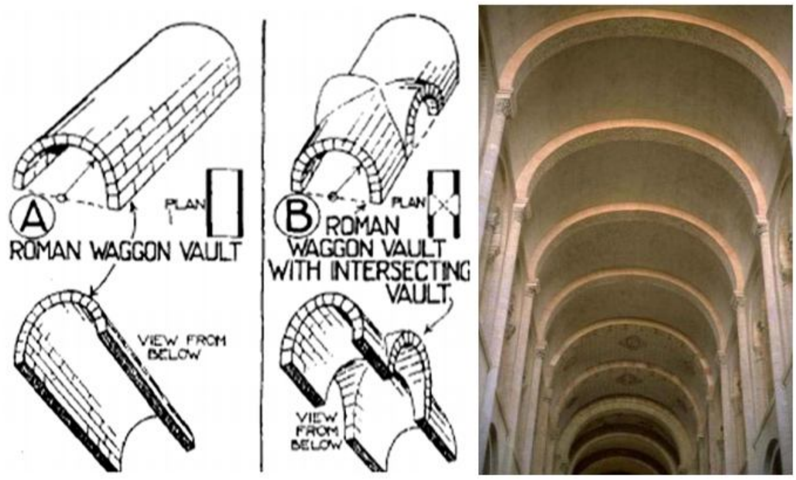


Fig. 1 – The barrel vault (Fletcher, 1961).

profiles are used for these elements. Important aspects for these types of structures are provided by the construction process, the elements shapes and the joints. Master-builders used different kinds of patterns for barrel vaulted structures. Obvious, the static and dynamic behavior of these structures are influenced by their particular pattern. In single curved vaults principal stresses situated along the curve are always compressive and the supporting system requires adequate weight to constrain large forces of expansion. If the thrust action transmitted by vaults is to high it may cause overturning and deformation of the supporting walls.

Diverse factors influence the structural behaviour, such as geometry, stiffness and mass distribution, chronological succession of the building works and past reconstructions. In order to investigate, through static and dynamic analysis, the lateral stiffnes of vaulted masonry churches two study cases were taken into consideration. The church of Bogdana Monastery from Rădăuți (Fig. 2) is the oldest stone religious building in Moldavia and was built in 1360's by the founder of the medieval independent state of Moldavia, Bogdan I. The church has a basilical plan, without towers, typical for early Moldavian architecture and adjusted to the orthodox cult. Built in 1494-1499 by Ioan Tăutu, chancellor of Moldavia under Stephen the Great, the church of Bălineşti (Fig. 3) is a massive construction made of stone masonry. It is a hall type church, with no lateral apses and the West wall of the pronaos and the Est wall of the altar have polygonal shape with three sides. The bell-tower, higher then the church, is on the South face, opposite the entry (Soveja & Gosav, 2013).

Fig. 2 – Bogdana Church.

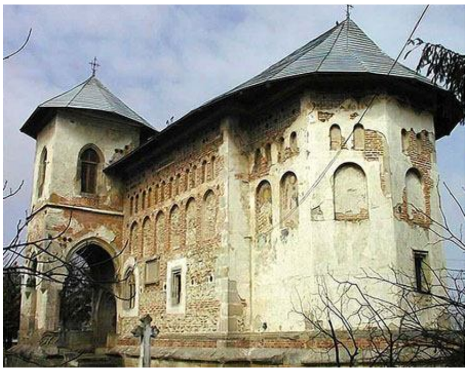


Fig. 3 – Bălineşti Church.

2. Structural Characteristics

Complete geometrical *in situ* survey of both churches were performed. In the structural analysis of the Bogdana church, the exornatex was not taken into consideration because it was built later and presently is separated from the rest of the structure. The church is 32 m in length and 12 m width, without measuring the butresses. The walls are 1.05...1.50 m thick and 9.4 m high made of stone masonry and lime mortar. The buttresses were demolished and rebuilt with ashlar, 75…85 cm thick, probably later because of the damage caused by earthquakes. The church is roofed with semi-cylindrical vaults on the length of the three naves (Fig. 4). The narthex and altar vaults are 1.6 m and 0.7m lower than the main vault, wich is divided in equal lengths by two archs placed in line with the columns. The thick at the vault capstone is 40 cm. Because of the damaged produced by the thrust of the main vault a steel rod was placed at the vault springer level. The material the vaults are built from is a porous rock, named "siga", with a very low weight in order to reduce the mass at the top of the church.

Fig. 4 – The vaulted roof of Bogdana Church.

The church of Bălineşti is a stone masonry construction with external walls of 1.3 m thickness and the interior transversal one of 1.1 m. The in-plane dimensions of the church are 22 × 9 m. Both narthex and naos are covered with barrel vaults divided by cross ribs in equal parts. Above the altar is a lower placed vault that continues with a semi-dome intersecting the east polygonal walls. The barrel vaults are made out of brick masonry, in two layers, with the total thick of 28 cm (Fig. 5). It is known that at some point a part of the vaults collapsed (probably those above the altar) and there where rebuilt with a smaller thickness.

Fig. 5 – The vaulted roof of Bălineşti Church.

2. Head Beams System

One of the rehabilitation solutions could consists of a system with girders (Fig. 6) on the walls cap with the purpose of stiffening, in horizontal plane, the upper part of the nave. Therefore, the capability of the structure to ensure the deformation compatibility of the structural walls and the risk of walls overturning because of the out of plane seismic action is improving. Also, the timber support of the roof could be fixed on the head beams. The girdles have the width equal with the width of the walls and the height of 25 cm.

In connection with the head beams, a spatial system of curved beams are placed on the both sides of the arches and at the base of the vaults in order to ensure their stability.

The head beams system allows further rehabilitation works with vertical steel ties in drilled holes, anchored at the upper part on the head beams and in concrete at the base of the structure. The reinforced concrete system is to be built on the existing masonry elements (walls, arches, vaults) without any changes on the existing form of the churches that would affect the solution reversibility and the integrity of the material.

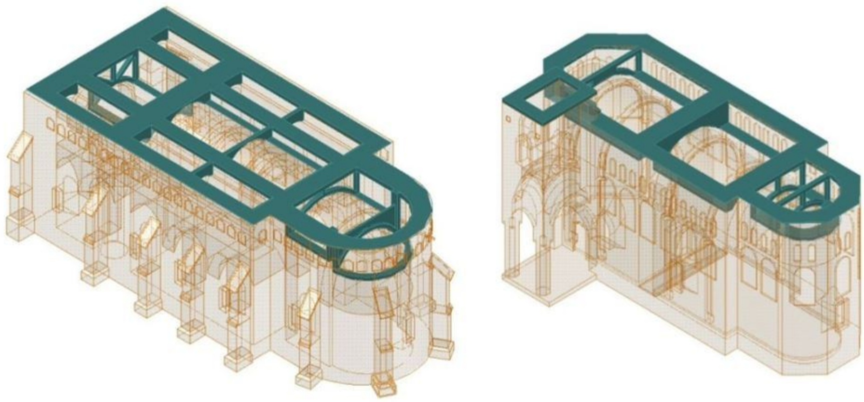


Fig. 6 – Head beams systems of Bogdana (left) and Bălineşti (right) churches.

3. Finite Elements Models

In order to investigate the lateral stiffnes of vaulted masonry churches and ways to improve the structural response to seismic actions, linear static and dynamic analysis were conducted on three-dimensional complexes of two churches previously presented (Fig. 7). The analysis models were developed by using Etabs V9.7.2. software.

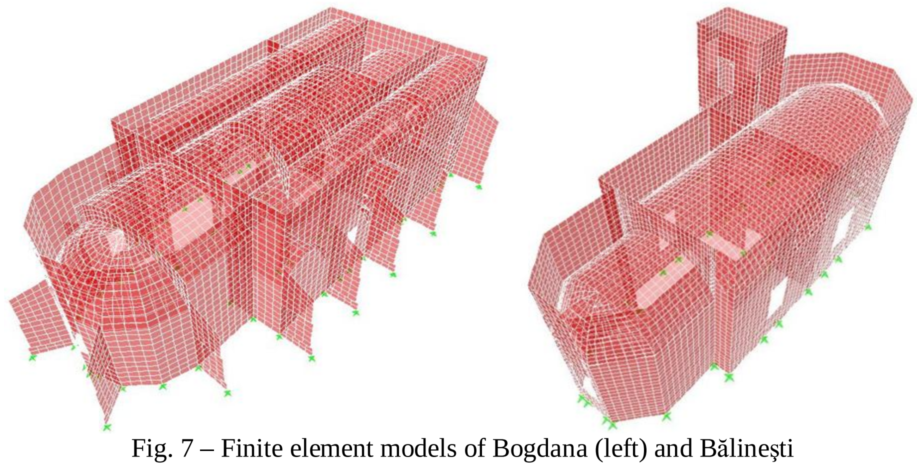


Fig. 7 – Finite element models of Bogdana (left) and Bălineşti (right) churches.

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. In this paper, because the analysed 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).

Compressive tests were carried out in laboratory on samples of stone and mortar extracted from the walls and vaults. The design values of the mechanical properties of the materials are obtained by considering the confidance factor and the material safety coefficient. The tensile strength and the modulus of elasticity were obtained from the masonry compressive strength. The design values are reported in Table 1. A response spectrum analysis was performed according to national codes. The peak ground acceleration was considered equal to ag = 0.16 g and the importance factor for historic monuments, $\gamma_I = 1.2$ (Soveja & Gosav, 2013; P1001/2006; P100/3-2008).

Table 1
Materials Design Values

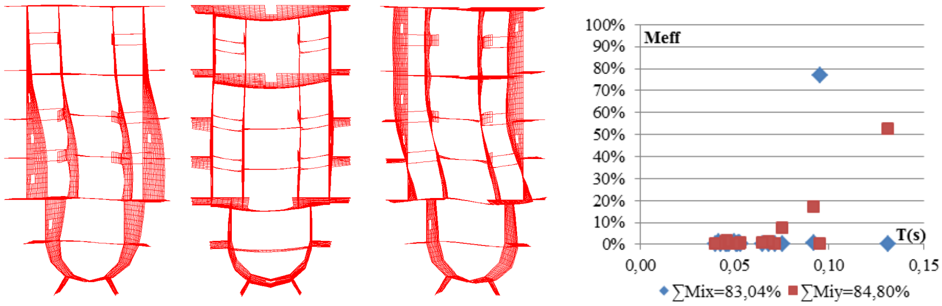
Church	Elements	f_d, [N/mm^2]	W, [kN/m^3]	E, [N/mm^2]
Bogdana	walls	2.28	23	6,328
	vaults	0.44	11.2	1,221
Bălinești	walls	2.52	23	6,978
	vaults	0.42	18	1,172

The dead loads of the masonry walls and vaults were automatically calculated by the program based on the dimensions of the structure and the specific weight and the live loads on the roof and vaults were considered 0.75 kN/m^2.

4. Modal Analysis

The modal analysis performed on spatial finite element models for Bogdana and Bălineşti churches revealed a rigid response, with vibration period values below 0.17 s and a relatively high values of modal participating mass ratios for the first 5 vibration modes. Also torsional deformations with significat modal mass ratios are present in both analysis.

The dynamic behavior of the two analysed masonry vaulted churches with a head beams system is summarized below. In Figs. 8 and 9 the first three modal shapes with the corresponding values of the period of churches and the first 20 vibration modes distribution in transversal and longitudinal direction are reported. In Tables 2 and 3 are plotted the modal participating mass ratios (individual mode and cumulative percent) for the first 5 vibration modes.



1st Mode
T = 0.131 s

2nd Mode
T = 0.095 s

3rd Mode
T = 0.091 s

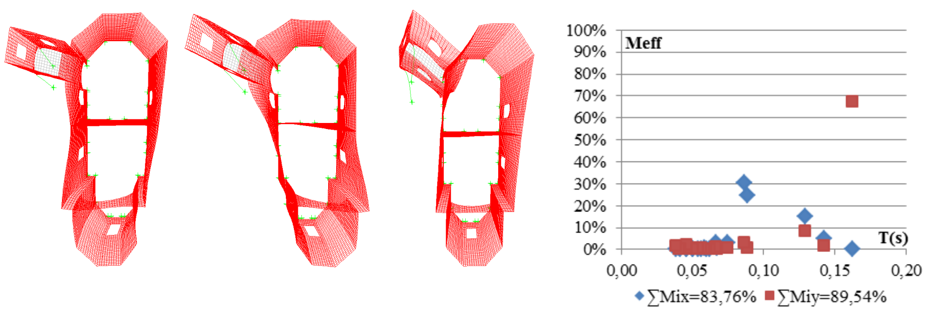
Distribution of the first 20 vibration modes

Fig. 8 – Bogdana – modal shapes and vibrations modes distribution.

Table 2

Bogdana – Modal Participating Mass Ratios

Mode	Period	Longitudinal direction (x-axe)		Transversal direction (y-axe)	
		M_{ix}/M_{tx}, [%]	$\sum M_{ix}/M_{tx}$, [%]	M_{iy}/M_{ty}, [%]	$\sum M_{iy}/M_{ty}$, [%]
1	0.1311	0.02	0.02	52.68	52.68
2	0.0955	76.75	76.77	0.30	52.98
3	0.0918	0.57	77.34	17.10	70.08
4	0.0752	0.00	77.34	7.65	77.73
5	0.0718	0.41	77.75	0.11	77.85



1st Mode
T = 0.162 s

2nd Mode
T = 0.142 s

3rd Mode
T = 0.129 s

Distribution of the first 20 vibration modes

Fig. 9 – Bălineşti – modal shapes and vibrations modes distribution.

Table 3
Bălineşti – Modal Participating Mass Ratios

Mode	Period	Longitudinal direction (*x*-axe)		Transversal direction (*y*-axe)	
		M_{ix}/M_{tx}, [%]	$\sum M_{ix}/M_{tx}$, [%]	M_{iy}/M_{ty}, [%]	$\sum M_{iy}/M_{ty}$, [%]
1	0.1624	0.45	0.45	67.34	67.34
2	0.1424	4.97	5.42	1.56	68.90
3	0.1292	15.07	20.49	8.37	77.27
4	0.0890	24.47	44.97	0.58	77.85
5	0.0869	30.41	75.37	2.89	80.74

5. Conclusions

Using the results from the modal analysis of two masonry vaulted churches with a head beams system of reinforced concrete, some conclusions have been established. Taking into account the first 5 vibration modes for each church it was obtained a total modal participating mass ratio of 77.5% on longitudinal direction and 77.85% on transversal direction for Bogdana church and 75.4% and 80.74% for Bălineşti church. Torsional deformations with significat modal mass ratios are present in both analysis, wich suggest a low torsional stiffness of the constructions because of the lack of „box behaviour". The first mode for both churches is on transversal direction with relatively small values of modal participating mass ratios (50.5% for Bogdana and 61.3% for Bălineşti) revealing that the dynamic response of the two analysed churches is affected by the local behaviour of the macro elements.

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COMPORTAREA STRUCTURILOR CU BOLȚI, CONSOLIDATE CU SISTEME DE CENTURI DIN BETON ARMAT

(Rezumat)

O problemă de mare importanță la nivel național şi internațional o constituie evaluarea şi reabilitarea clădirilor de cult şi a celor din patrimoniu datorită proporției ridicate din fondul construit pe care o reprezintă, vechimii acestora şi necesității îmbunătățirii nivelului de siguranță seismică cu scopul de a face față prezentelor condiții de utilizare. În cazul bisericilor vechi din zidărie, bolțile şi cupolele acoperişului nu asigură compatibilitatea deformatiilor pereților structurali şi împiedicarea răsturnării aestora pentru forțe seismice perpendiculare pe plan. În lipsa unor legături rigide în plan orizontal la nivelul acoperişului, distribuția forțelor seismice se realizează proporțional cu masa zidurilor, fără a se asigura conlucrarea acestora. În acest articol se analizează, cu ajutorul unui program de calcul cu element finit, două structuri de rezistență a unor vechi biserici din zidărie la care s-a adăugat un sistem spațial de grinzi şi centuri cu rol de rigidizare la partea superioară a zidurilor şi în dreptul bolților de acoperiş. Sunt prezentate şi comentate formele şi perioadele modurilor de vibrație, precum şi valorile şi distribuția maselor modale aferente.