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Seismic assessment of typical historical masonry churches in the Banat region, Romania - Part II

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Abstract

This work focuses on the built heritage in Romania, with particular attention to five Orthodox masonry churches located in the Banat region, whose structural configuration is characterized by a unique nave and a bell tower included into the main façade. In a companion paper the seismic numerical investigations of Romanian masonry churches according to the Romanian regulations is presented. In this paper, firstly, a seismic performance comparison of the five churches with simplified risk assessment methods is conducted. Then, the preliminary results of a case study, obtained with both a macro-elements approach and a FEM model, are illustrated and commented. The numerical results here discussed belong to on-going research campaign addressed to highlight the main characteristics of the seismic performance of the Romanian churches, also including the damage observed under seismic events, as well as to compare the results to each other.

Keywords: Romanian historical masonry churches; seismic assessment; simplified methods; local failures; non-linear analyses

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1. Introduction

Our cultural heritage is increasingly threatened by environmental disasters, such as volcanic eruptions, floods, landslides and last, but not least, earthquakes. This has led to a very thorough study of environmental phenomena and the consequences that these have had on the building heritage, in order to predict the possible damage and to promptly operate for its conservation. Within the cultural heritage, without any doubt churches represent a construction typology worthy of investigation, because of their construction systems extremely vulnerable with respect to seismic actions, as demonstrated by the damage surveyed after the last earthquakes, even of moderate intensity.

In a companion paper (Part I, Lo Monaco et al. 2022) numerical investigations on the seismic assessment of Romanian masonry churches according to the Romanian regulations are performed. Instead, this work (Part II) focuses on seismic risk assessment on five Orthodox brick masonry churches located in the Banat region in Romania. Moreover, preliminary results obtained with macro-elements approach and with a global 3D FEM model are illustrated. The work presented is in accordance with the multi-level approach proposed by the Italian directive G.U. n. 47 (2011) and is addressed to compare the results obtained with different approaches followed. In this paper the preliminary results of an ongoing numerical simulations campaign are illustrated.

2. Background

Orthodox churches, as observed in Mosoarca and Gioncu (2013), frequently record the greatest damages in correspondence of nave and apse altar. Damages detected on churches in the Banat area after two earthquakes occurred in July and December 1991 have suggested a division of the church in five independent structural portions (indicated as rigid-blocks): apse, three blocks along the nave in correspondence of the openings, and the last one represented by the façade-bell tower (Fig. 1a and 1b). Both earthquakes of 1991 were characterized by very short period of vibration (0.2-0.3 sec), in which the first cycle was the most powerful. Moreover, the vertical components were not negligible. It is worth to note that, although characterized by a more complex spatial organization and larger dimensions, the seismic damages of the Italian churches observed after the last earthquakes are quite similar to the ones observed for Banat churches. Therefore, this similitude allows us of extending the Italian macro-element approach to the Romanian Orthodox churches in the Banat region here considered. Finally, the Romanian hazard map shows a variable ground acceleration a_g between 0.10g and 0.25g in the Banat region, referred to a return period T_R = 225 years [P_{VR} = 20% in 50, Romanian Seismic Design Code, Part I (2013)] (Fig. 1c).

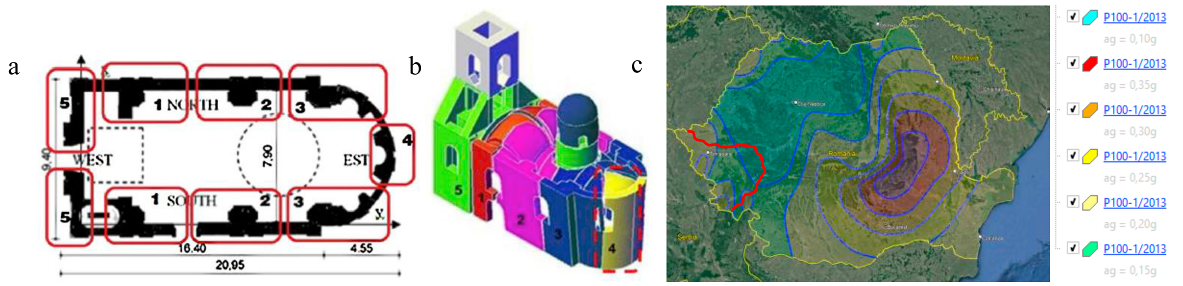


Fig. 1. (a) Division in rigid blocks of a typical Orthodox church plan; (b) rigid blocks in a 3D model; (c) Romanian hazard map.

3. Seismic assessment at a territorial level of five churches in the Banat region

Fig. 2a shows the location of the five churches considered in this study, placed in the Banat region. In particular, four churches are located in the Timiș district, and one in the Caraș-Severin district.

The first part of the work was focused on the documentation research of the architectural drawings and pictures, giving information about the churches' structures, previous damages and interventions (if any). The main elements of an Orthodox church are here listed and indicated in Fig. 2b, by referring to Belint church: *narthex* (also named pronaos, the area preceding the temple), *bell tower*, *central nave* or *naos* (the area where the celebration may be attended), *sanctuary* (the area where the altar, priests and deacons are collocated) and *iconostasis* (the wall full of icons separating the naos and the sanctuary). Table 1 reports pictures and plans of the churches considered.

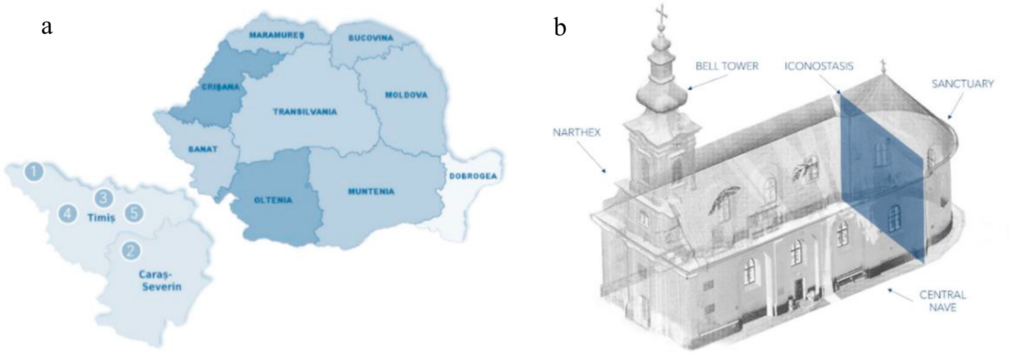
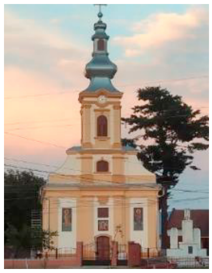
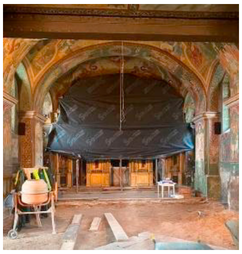
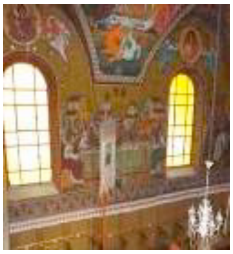
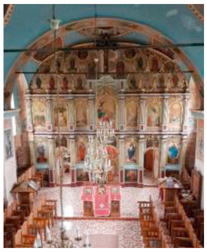
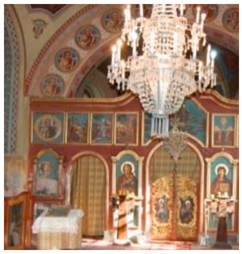
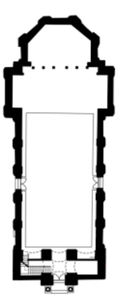
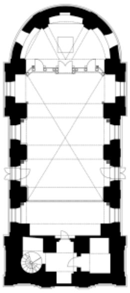
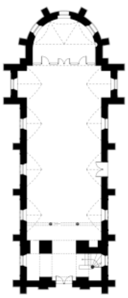
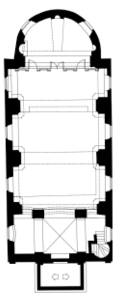
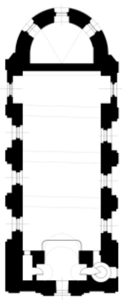


Fig. 2. (a) Location of the five churches analyzed in the Romanian Banat region; (b) main elements of an Orthodox church.

Table 1. Five churches in Banat Region.

1 Pogorârea Sfântului Duh (Holy Spirit Descent)	**2** Sfint Nicolae (Saint Nicholas)	**3** Sfantul Nicolae (Saint Nicholas)	**4** Sfântul Gheorghe (Saint George)	**5** Învierea Domnului (Jesus Resurrection)
Municipality of Cenad	Municipality of Bocsa	Municipality of Bencecu de Jos	Municipality of Beregsău Mare	Municipality of Belint
				
				
				

The structural configuration of all these churches is characterized by rectangular plan, bearing walls made of brick masonry (in Saint Nicholas Church stone masonry is also present), bell tower incorporated in the main façade made of brick masonry and with a wooden spire at the top, narthex with a mezzanine, pitched wooden roof, masonry vaults (even if in some case also non-structural/false vaults are present, as in the church in Cenad and the church in Bencecu de Jos), a short transept and a circular or polygonal apse.

The **Holy Spirit Descent Church** was built around 1888 on a flat rural area of Cenad. The nave is introduced by a little portal and ending with a deep transept and a semi-octagonal apse. It is composed of 70 cm thick walls and barrel vault with lunettes. The bell tower reaches a height of 26.15 m. The church shows cracks on walls, damaged plaster and paintings. A previous intervention with metal ties was made to counteract the horizontal thrust of vaults.

The **Saint Nicholas Church** in the little city of Bocsa, was built from 1795 to 1911 with the bell tower reaching a height of 35.33 m. The church has 1 m thick walls and brick masonry vaults. The excellent state of conservation is justified by the restoration of 2016, involving foundations, floors, roofs and the use of metal ties.

The other **Saint Nicholas Church** is located on a hilly area of Bencecu de Jos. It was built in 1899. This building, whose bell tower reaches the height of 23.27 m, is realized with 55 cm thick walls and a plasterboard and wooden plank barrel vault. In 2015 an intervention repaired the façade and the roof.

The **Saint Georg Church** in Beregsău Mare was built from 1793 to 1810. It insists on a flat rural area. The bell tower reaches the height of 27.96 m and the walls have a thickness of 60 cm. The metal ties confirm the need to counteract the thrust of the brick masonry vaults. The church shows cracks on walls, damaged plaster and paintings.

Finally, the **Jesus Resurrection Church** of Belint, built in 1797, is located in a flat rural area. The height of the bell tower is 25.80 m, while the thickness of walls reaches 170 cm. The church is covered by a system of barrel brick masonry vaults and arches. From 2014 to 2020 the building was interested by a complete restoration which, involved foundations, bell tower, walls, roofs, openings and finishes. Before the intervention, the church showed important vertical cracks in the apse area, in correspondence of the windows.

3.1. LV0 and LV1 analysis of five churches

The Italian directive G.U. n. 47 (2011) proposes the use of a multi-level approach (LV1, LV2 and LV3) for seismic risk assessment of the cultural heritage, consisting of three Levels of Valuation (LV) requiring an increasing amount of information with an increasing refinement level. In addition, and coherently with this multi-level approach, recently in Dìaz Fuentes (2016) and D'Amato et al. (2019 and 2020) a simplified level of evaluation, indicated as LV0, has been proposed. LV0 and LV1 are useful for conducting a seismic assessment at a territorial scale. As regards LV0, it provides a Risk score (***R***), resulting from the combination of the Hazard (***H***) and the Vulnerability (***V***), by means of the Eq. (1). Whereas, the LV1 proposed by the Italian directive requires the application of the Eqs. (2-4).

$$R = [H + 1] \times V \quad (1)$$

$$i_v = \frac{1}{6} \cdot \frac{\sum_{k=1}^{28} \rho_k \cdot (v_{k_i} - v_{kp})}{\sum_{k=1}^{28} \rho_k} + \frac{1}{2} \quad (2)$$

$$a_{DLS} S = 0.025 \cdot 1.8^{2.75 - 3.44 i_v} \; [g] \quad (3)$$

$$a_{LSLS} S = 0.025 \cdot 1.8^{5.1 - 3.44 i_v} \; [g] \quad (4)$$

The vulnerability index i_v is related to all the collapse mechanisms that may occur in the analyzed church, varying between 0 and 1. r_k is the weight of each collapse mechanism, while v_{ki} e v_{kp} are the scores assigned to the *k-th* mechanism, respectively related to evaluated vulnerability and to any seismic-resistant device. a_{DLS} and a_{LSLS} are the calculated ground accelerations for the Damage Limit State (DLS) and the Life-Safety Limit State (LSLS), respectively, which are multiplied by the stratigraphic amplification *S* depending on the foundation soil. Fig. 3 shows the comparison between LV0 and LV1 analyses carried out on the five churches studied. As for the LV0, the Fig. 3a reports the scores related to *V*, *H* and *R* for the churches investigated. While, as for the LV1, Fig. 3b-3d report, respectively, the vulnerability index i_v and the resulting a_gS at DLS and LSLS. It can be noted that there is an agreement between the results obtained with the LV0 and the LV1. In this case, the most vulnerable church results the Cenad church, while on the contrary the least vulnerable is the Belint church. It is pointed out that the higher the vulnerability index the smaller the ground acceleration estimated. The predicted a_gS ranges from 0.028g to 0.042g for the DLS, and from 0.113g to 0.169g for the LSLS. In the case analyzed, the expected a_g on rock soil, having a return period T_R =225 years, results equal to 0.15g for churches in Belint and Bocsa, and to 0.20g for the other ones. Therefore, if the LSLS is assumed for T_R =225 years, although in this study the stratigraphic coefficient S is unknown, it may be concluded that no one of the churches investigated satisfies the LSLS verification.

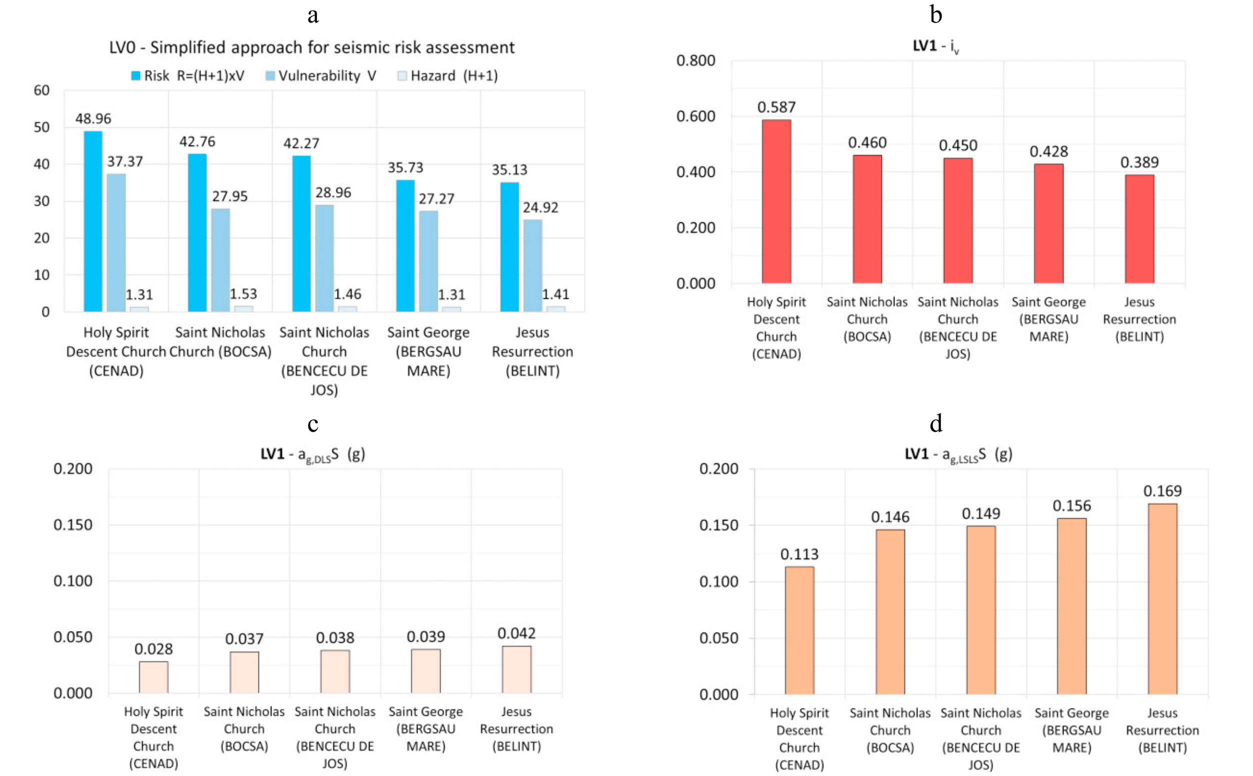


Fig. 3. (a) R, V and H scores for LV0; (b) i_v for LV1; (c) $a_{g,DLS}S$ for LV1; (d) $a_{g,LSLS}S$ for LV1.

4. Seismic assessment of the Church "*Învierea Domnului*"

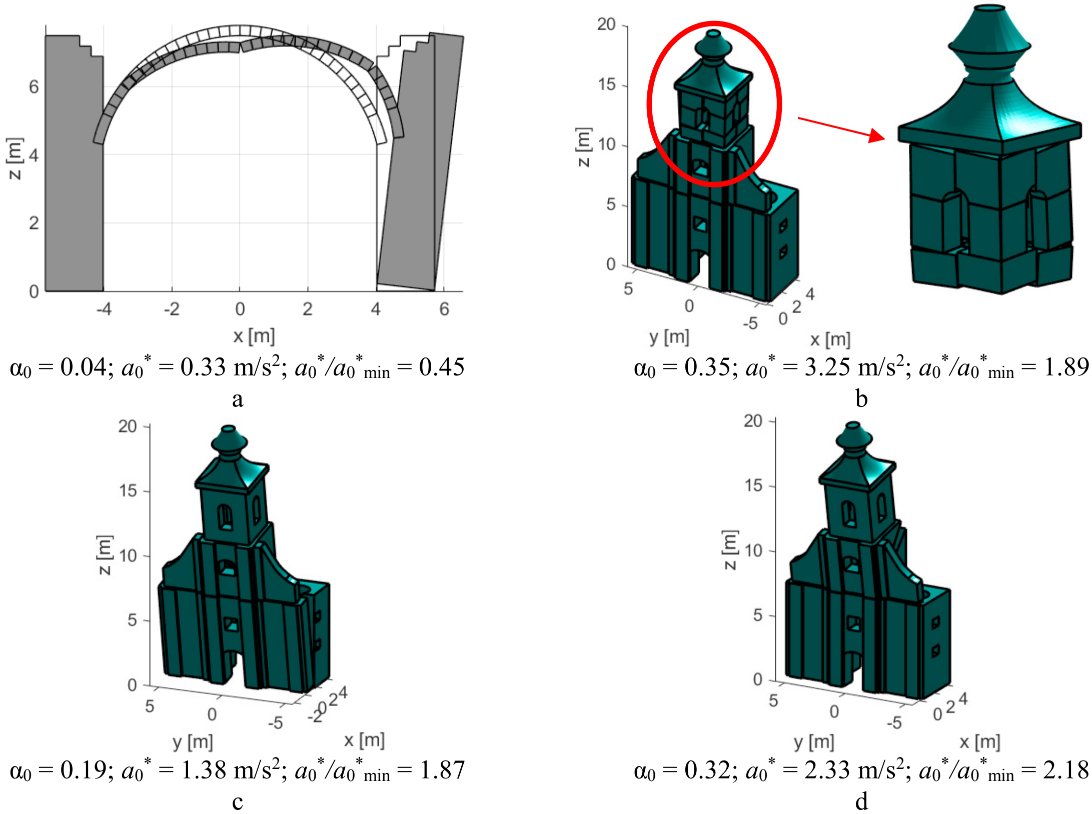
In this section the preliminary results of the seismic assessment of the "*Învierea Domnului*" church in Belint are shown. According to the Italian directive G.U. n. 47 (2011), the numerical simulations are carried out by applying the LV2 and the LV3 approach. In particular, the LV2 involves a macro-element analysis (Doglioni et al. 1994, Lagormarsino 2012), where the failure modes of some architectural parts are studied independently of each other. Whereas the LV3 approach regards the implementation and the analysis of a global FEM 3D model in order to compare among them the obtained results (Formisano et al. 2022). In the following only the preliminary results obtained in this on-going research are obtained.

4.1. LV2 analysis - Local failures assessment through limit analysis

By taking in account the Belint church as case study, some classical local mechanisms are analyzed through a limit analysis approach based on the kinematic theorem. Each local mechanism is studied by considering a representation of the involved structural elements into few macro-blocks that remain rigid and infinitely resistant and respond to the horizontal actions through mutual roto-translations. The mechanism is so described in terms of a discontinuous velocity field, in which the discontinuities are localized at the interfaces between the rigid macro-blocks. The failure criterion at the interface can reproduce both the classical no-tension material conditions, i.e. null tensile resistance and infinite resistance to crushing and sliding (Heyman, 1966), or a more specific Mohr-Coulomb behaviour with tension cut-off and cap in compression. Once defined a distribution of permanent and variable loads, the latter depending on a load multiplier and typically represented as a distribution of horizontal load proportional to masses, the discontinuous velocity field identifying the local failure mechanism can be obtained by solving a simple linear programming problem.

In order to take into account the actual geometry of curved structural elements, such as arches and complex double curvature vaults, in the adopted procedure each macro-block is represented through Non-Uniform Rational B-Spline (NURBS) parametric functions (Piegl and Tiller, 1996). This strategy resulted particularly suited for historical masonry structures (Grillanda et al, 2022), since it allows to work directly with geometries represented in the modeling software by avoiding refined discretization through smaller regular elements.

In this study, some local mechanisms for the Belint church are investigated (Fig. 4). In particular, the load bearing capacity of the arches within the nave are studied. The arch is considered supported by two abutments, whose thickness coincide with the thickness of the longitudinal nave walls, whereas the presence of the barrel vault is included through a distributed mass at the extrados of the arch. Then, some local mechanisms are investigated for the tower, such as the simple overturning (global and partial) and the collapse of the belfry. Given the walls massive thickness of the façade-tower system, the resulting safety indexes result higher than 1. In future, more complex local mechanisms will be investigated, considering for instance other typical failures for towers (Milani, 2019).



$\alpha_0 = 0.04$; $a_0^* = 0.33$ m/s^2; $a_0^*/a_{0\,min}^* = 0.45$ (a)

$\alpha_0 = 0.35$; $a_0^* = 3.25$ m/s^2; $a_0^*/a_{0\,min}^* = 1.89$ (b)

$\alpha_0 = 0.19$; $a_0^* = 1.38$ m/s^2; $a_0^*/a_{0\,min}^* = 1.87$ (c)

$\alpha_0 = 0.32$; $a_0^* = 2.33$ m/s^2; $a_0^*/a_{0\,min}^* = 2.18$ (d)

Fig. 4. Local mechanisms investigated for the Belint church: (a) collapse of the arch in the central nave; (b) belfty failure; (c) global and (d) partial overturning of the tower-façade system.

4.2. LV3 analysis - Global FEM 3D model

A global FEM 3D model of the Belint church has been implemented for numerical simulations with the software MIDAS FEA NX (2022). In this study the results of the modal analysis are illustrated, while the non-linear simulations are still on-going and the obtained results will be completed and shown in future works. For modal analysis the masonry has been assumed as isotropic material. Fig. 5 illustrates the modal shape obtained. In particular, Fig. 5a-c depict the 1st and the 6th vibration mode shape, that are the first two translational modes with the higher mass ratio percentage along the X-direction, having respectively T1=0.25 s (%Mass ratio=14.14%) and T6= 0.1 s (%Mass ratio=47.12%). Whereas, the Fig. 5b-d show the 2nd and the 8th vibration mode shape with the higher mass ratio percentage along the Y-direction, having respectively T2=0.20 s (%Mass ratio=56.46%) and T8= 0.097 s (%Mass ratio=8.84%). As it was easy to expect, the obtained results confirm that the projecting part of the bell-tower is more deformable than the other parts of the church. In fact, the 1st mode is substantially the local mode of the projecting part that behaves as a cantilever. In the 6th mode also the church is involved. Along the Y-direction, the 2nd and the 8th modes regard the church nave thanks to the lateral walls out-of-plane deformability.

As preliminary investigation, Fig. 6 illustrates the normal stresses values obtained with a spectrum analysis carried out along the two principal directions X and Y. The seismic action has been defined according to the Romanian design code (Code de proiectare seismică, 2013) with a PGA equal to 0.15g. The results highlight that the seismic action provokes tensile stresses at the base and top of the lateral walls and apse, and at the base of the main façade and of the projection part of the bell tower. In these zones, including the effects of the vertical loads and of the masonry degradation, due for instance to a previous vertical seismic action, a detachment may arise facilitating the formation of the macro-elements. More detailed analyses, including the material non-linearities and also masonry cracking, will be conducted in future.

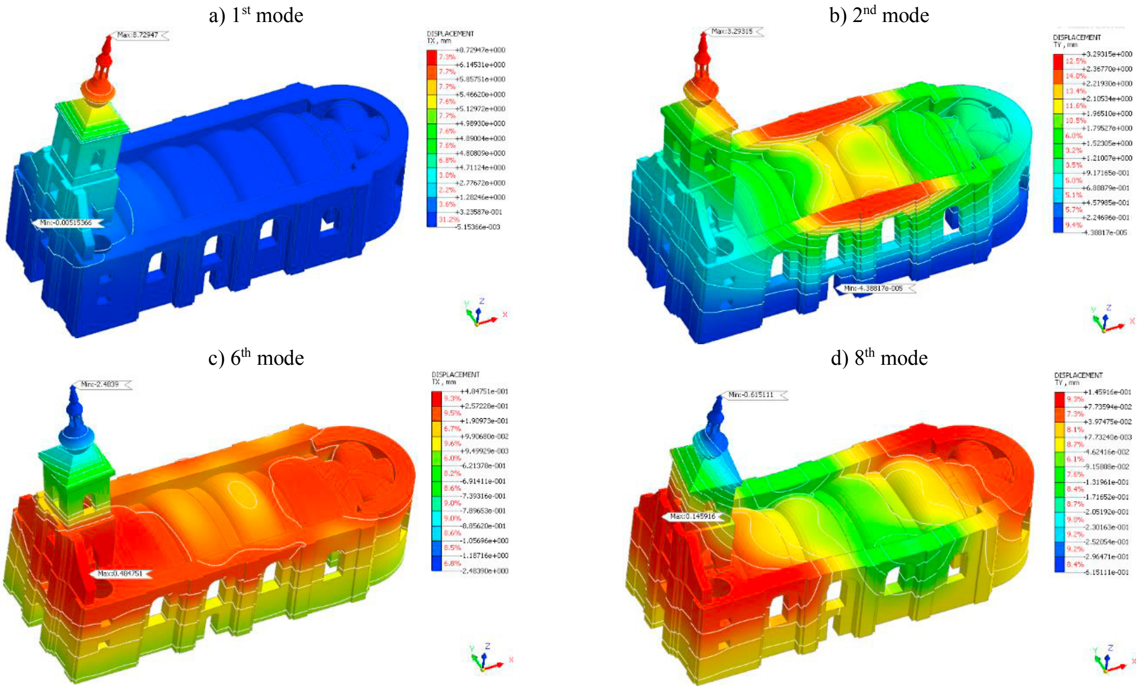


Fig. 5 (a) M1; (b) M6; (c) M2; (d) M8

5. Conclusions and future results

In this study the typology of the masonry Romanian churches was investigated. In particular, five churches were considered for seismic analysis at a territorial level. Then, some preliminary results related to a case study were illustrated. In particular, the results obtained with a macro-elements approach and a global FEM 3D model were presented. The study will continue in performing non-linear analyses on the five churches considered in order to compare and establish a correlation among the results obtained with different approach considered.

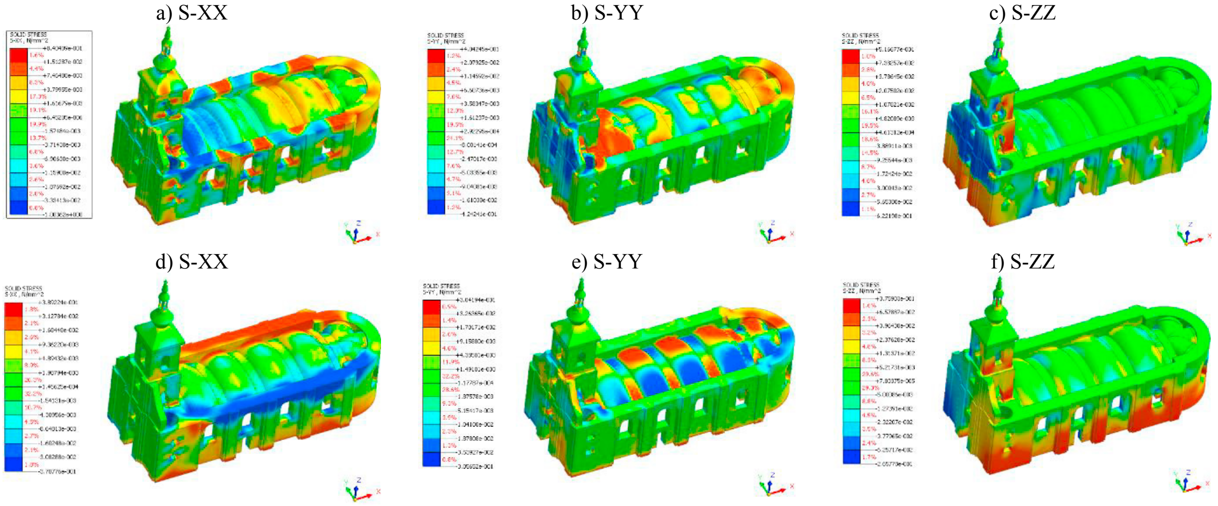


Fig. 6 Response Spectrum Analysis (RSA) along X: a), b) and c) and along Y: d), e) and f)

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