Vulnerability Assessment of Historical Churches in Banat Seismic Region, Romania

Iasmina Onescu[1](✉), Anna Lo Monaco[2], Mihai Fofiu[1], Nicola Grillanda[3], Marius Mosoarca[1], Michele D'Amato[2], and Antonio Formisano[4]

[1] Department of Architecture, Faculty of Architecture and Town Planning, Politehnica University of Timisoara, P-ta Victoriei No. 2, Timisoara, Romania
iasmina.onescu@upt.ro

[2] Department of European and Mediterranean Cultures, Architecture, Environment and Cultural Heritage (DiCEM), University of Basilicata, Via Lanera 20, 75100 Matera, Italy

[3] Department of Civil and Structural Engineering, University of Sheffield, Mappin Street, Sheffield S1 3JD, UK

[4] Department of Structures for Engineering and Architecture, School of Polytechnic and Basic Sciences, University of Naples Federico II, Naples, Italy

Abstract. Romania is a country located in Europe, with moderate seismicity and a very large number of historical churches. Banat region is the second most important seismic area in the country, located in the western part, characterized by shallow earthquakes of crustal type. In Banat area there are many historic churches, both Orthodox and Catholic. The majority of the churches are mostly with a central nave, made in masonry, with masonry vaults and complex wooden frameworks. They also present architectural-artistic details, such as paintings made by Austrian, Serbian and Romanian painters. Many of them have suffered different types of structural damages after past earthquakes. The damage types are different, depending on the type of earthquake and on the architectural conformation. The present paper investigates the seismic vulnerability for six historic churches in Banat area and presents the results of various empirical and numerical analysis and investigations. The analysis identifies the specific vulnerable points of the historic religious structures, illustrating the seismic vulnerability of the churches with central nave in Banat seismic area. Moreover, the paper brings out the importance of investigating the seismic behavior of religious buildings, as they are permanent part of each local community, and they present an important cultural value.

Keywords: churches · vulnerability assessment · cultural value · seismic behavior · masonry

1 Introduction

1.1 Opportunity of the Research Theme

Churches represent a complex architectural program, with important religious and cultural value for the local communities. They are one of the most representative architectural objects, that are kept in good shape even in the present, even though the historical

Y. Endo and T. Hanazato (Eds.): SAHC 2023, RILEM Bookseries 46, pp. 1146–1158, 2024.
https://doi.org/10.1007/978-3-031-39450-8_93

ones were built hundreds of years ago, before the existence of any design codes, in wood, stone or masonry.

In Romania, one of the most representative architectural edifices are the religious ones, as the Orthodox religion is very present in the life of the people. There are thousands of Orthodox churches on the territory of Romania and also several Catholic and other religion churches. The majority are well preserved and still in use, continuing to represent a point of interest for the community life, especially in the rural areas of Romania.

Because of the complex architectural and structural configurations, as well as because of the valuable architectural-artistic, symbolic and cultural components, the vulnerability assessment of such edifices is a very difficult task, especially to earthquakes, which represents one of the most probable hazards of the country. The typical types of damage can be very different, depending on the structural configuration and earthquake type [1–4]. Several studies were made in the past for the Orthodox and Catholic churches in Banat area based on the failure rigid blocks for churches type [5], as well as more recently, based on comparison between numerical analysis and real damages observed after past earthquakes [6].

1.2 Seismicity of the Area

The selected investigated churches are located in Banat seismic area, which represents the second most important seismic zone of Romania.

The overlaying maps of the European earthquake hazard map [7] and the peak ground acceleration map according to the Romanian legislation [8], there can be noticed the fact that Banat area seems to have its own epicenters for earthquakes, as presented in Fig. 1b [6].

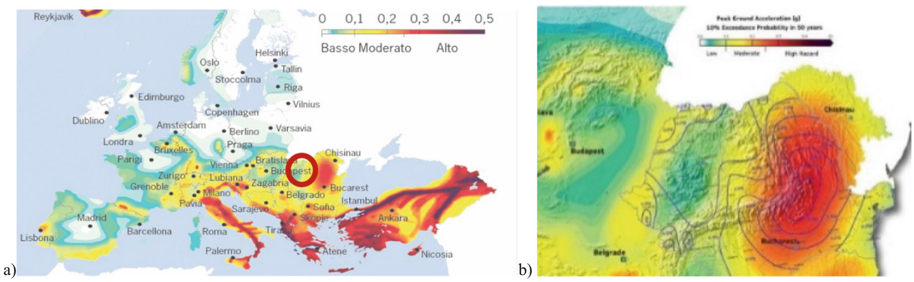


Fig. 1. a) Localization of Banat seismic area on the European seismic hazard map [7]; b) overlayed map for Romania [6].

The seismicity of the area is a moderate one, with shallow earthquakes of crustal type, small focal depths and powerful vertical forces [9]. The maximum recorded magnitudes in the area are of 5.6 M_W, while the peak ground acceleration varies from 0.15 g to 0.20 g, depending on the exact location in Banat seismic area. To determine the most probable macroseismic intensity for the churches in this area, there was applied Eq. 1 [10], illustrating a most probable macroseismic intensity VIII EMS-98 for the regions with PGA = 0.15 g, and IX EMS-98 for the regions with PGA = 0.20 g.

$$\ln(\mathrm{PGA}) = 0.24 \times I_{\mathrm{EMS-98}} - 3.9 \quad (1)$$

2 Case Study Churches

The paper investigates six Orthodox masonry churches that are considered to be representative for Banat area. Five of them are located in Timis county, while one of them is located in Caras-Severin county, as illustrated in Fig. 2.

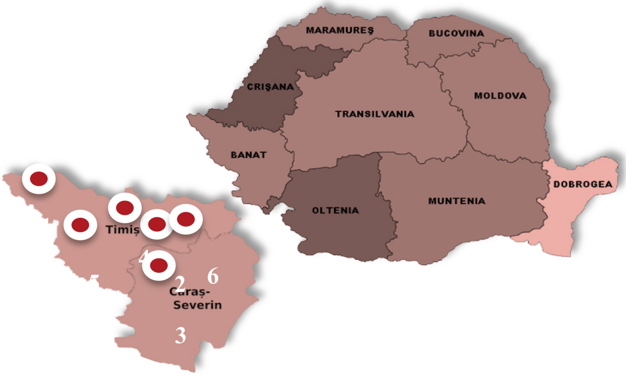


Fig. 2. Localization of the investigated churches.

2.1 Architectural and Structural System

The selected churches are very similar from the architectural point of view, as they are representative for the architectural style of the religious buildings in Banat area, that were built in the XVIII-XIX Century. They are all built following a rectangular plan and a unique nave.

The architecture of the churches is based on some representative elements of the Orthodox buildings, such as the pronaos (also called narthex), the naos (also called the central nave), the iconostasis (which is the wooden wall that separates the naos from the altar), the altar (sanctuary) and the bell tower, which is always located in the main façade, centrally. The architectural typical configuration of the Orthodox churches in Banat area is illustrated in Fig. 3 [11].

All six investigated religious edifices are made in masonry clay brick with lime, with thick perimetral masonry walls. The foundations are made in masonry, only in one case are made in stone, and are continuous under the masonry walls. The bell tower is usually incorporated in the main façade and is made in masonry and a wooden spire at the top. The pronaos presents a mezzanine. There can be found masonry arches and

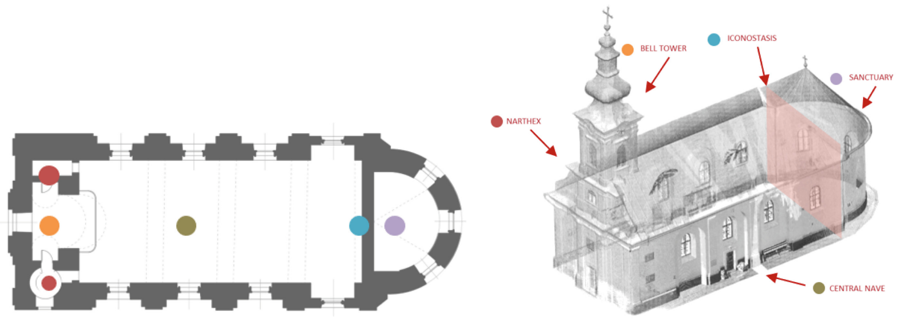
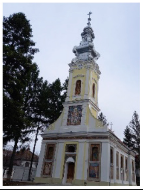
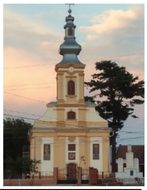
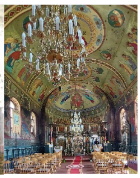
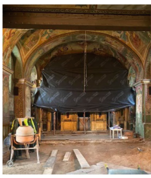
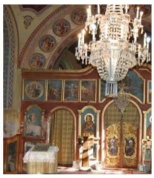
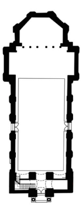
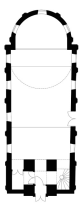
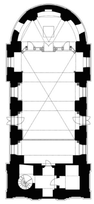
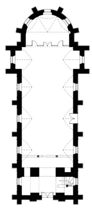
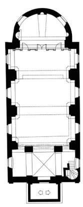
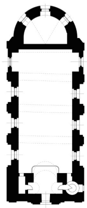


Fig. 3. Architectural typical configuration of the investigated churches [11]

vaults, which are usually structural, but can be also non-structural, built only for an architectural reason, as in the churches in Bencecu de Jos, Chizatau and Cenad. The roof is always a pitched wooden framework roof, while the altar is circular or hexagonal. The exact structural configuration of each church can be seen in Table 1 and Table 2 [11].

Table 1. Structural configuration of the investigated churches [11].

1 Pogorârea Sfântului Duh (Holy Spirit Descent)	**2** Nasterea Maicii Domnului (God's Mother Nativity)	**3** Sfintul Nicolae (Saint Nicholas)	**4** Sfantul Nicolae (Saint Nicholas)	**5** Sfântul Gheorghe (Saint George)	**6** Învierea Domnului (Jesus Resurrection)
Municipality of Cenad	Municipality of Chizatau	Municipality of Bocsa	Municipality of Bencecu de Jos	Municipality of Beregsău Mare	Municipality of Belint
					
					
					

2.2 Decay

Almost all buildings present vertical cracks on the exterior facades, in the proximity of the openings. In some cases, during on-site inspection, there were observed cracks in the masonry vaults and arches. In some cases, some cracks between the tower bell and the longitudinal walls were noticed. In general, the cracks were caused by the different settlements and are presented in Fig. 4. Other decays were observed at a non-structural level, such as damaged plaster and paintings, superficial plaster cracks. A synthesis of the construction details and observed damages is presented in Table 2.

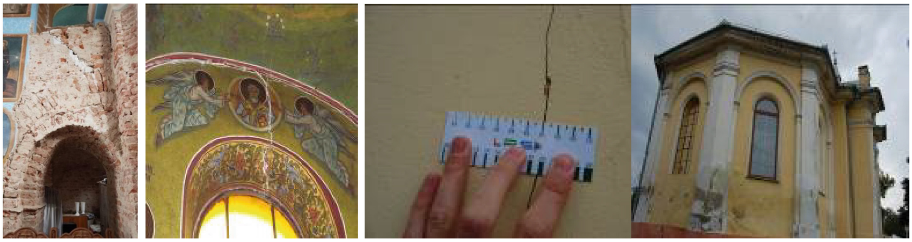


Fig. 4. Damage and cracks observed on the investigated churches.

Table 2. Synthesis of the decay observed on the investigated churches.

1	Construction period and location: 1888, flat rural area of Cenad Bearing walls material and thickness: brick masonry, 70–75 cm Vaults: wooden barrel vault with lunettes (false-vault) Bell tower height: 26.15 m Damages recorded: cracks on walls, damaged plaster and paintings	4	Construction period and location: 1899, hilly area of Bencecu de Jos Bearing walls material and thickness: brick masonry, 55–75 cm Vaults: plasterboard and wooden plank barrel vault with lunettes Bell tower height: 23.27 m Damages recorded: cracks on walls, damaged plaster and paintings
2	Construction period and location: 1827, flat rural area of Chizătău Bearing walls material and thickness: brick masonry, 57–97 cm Vaults: wooden barrel vaults and arches Bell tower height: 23.21 m Damages recorded: cracks on walls, damaged plaster and paintings, cracks between tower walls and longitudinal walls	5	Construction period and location: 1793–1810, flat rural area of Beregsău Mare Bearing walls material and thickness: brick masonry, 35–75 cm Vaults: brick masonry barrel vaults and arches Bell tower height: 27.96 m Damages recorded: cracks on walls, damaged plaster and paintings
3	Construction period and location: 1795–1911, city of Bocsa Bearing walls material and thickness: stone-brick masonry, 100–160 cm Vaults: brick masonry barrel vaults and arches Bell tower height: 35.33 m Damages recorded: damaged plaster and paintings	6	Construction period and location: 1797, flat rural area of Belinț Bearing walls material and thickness: brick masonry, 70–170 cm Vaults: brick masonry barrel vaults and arches Bell tower height: 25.80 m Damages recorded before interventions: vertical cracks in the apse area

3 Vulnerability Assessment

3.1 Empiric Vulnerability Assessment

The vulnerability assessment of the six Orthodox churches in Banat area was determined in various ways. One of the applied methodologies is a well-known European method, developed by Benedetti and Petrini [12] and calibrated for Banat area by Onescu and Mosoarca [9]. Moreover, the same methodology was developed by Onescu [13] to consider not only the structural parameters, but also the architectural-artistic, urbanistic and socio-economic ones. The assessment is obtained following a visual inspection and a fulfillment of a vulnerability form, which contains 37 individual parameters. The first 10 parameters refer to the structural assessment and they represent exactly the existing methodology of Benedetti and Petrini. The other parameters represent the original contribution of the authors Onescu and Mosoarca and they consider the cultural value of the investigated buildings. The vulnerability form indicates a final vulnerability index, which is obtained as the sum of each individual score of the assessed vulnerability class multiplied by an associated weight, as in Eq. 2 and Eq. 3 [10]. The final vulnerability form is presented in Table 3.

$$I_{V\ STRUCT} = \sum_{i=1}^{10} s_i \times w_i \tag{2}$$

$$I_{V\ CULT} = 0.70 \times \sum_{i=1}^{10} s_i \times w_i + 0.15 \times \sum_{i=11}^{28} s_i \times w_i + 0.10 \times \sum_{i=29}^{33} s_i \times w_i + 0.05 \times \sum_{i=34}^{37} s_i \times w_i \tag{3}$$

The mean damage is obtained following Eq. 4, so there can be determined the most expected damage state for the expected macroseismic intensity for each church [10] and was previously adapted by the authors for Banat area [9].

$$\mu_D = 2.5\left[1 + \tanh\left(\frac{I + 12.50 \times V_{CULT} - 13.1}{\Phi}\right)\right] \tag{4}$$

Table 3. Vulnerability form for empirical vulnerability assessment.

%	Criteria	No	Element	Class				Weight
				A	B	C	D	
70%	STRUCTURAL	1	Vertical structure organization	0	5	20	45	1.00
		2	Vertical structure nature	0	5	25	45	0.25
		3	Type of foundation and location/soil	0	5	25	45	0.75
		4	Distribution of structural elements in plan	0	5	25	45	1.50
		5	Regularity in plan	0	5	25	45	0.50
		6	Regularity in elevation	0	5	25	45	1.00
		7	Floor type	0	5	15	45	0.75
		8	Roofing	0	15	25	45	0.75
		9	Other details	0	0	25	45	0.25
		10	Conservation state	0	5	25	45	1.00
15%	ARCHITECTURAL ARTISTIC	11	Representative architectural style for the area	0	10	15	25	1.50
		12	Age, importance of the build époque	0	10	15	25	1.20
		13	Original woodwork/joinery	0	10	15	25	1.00
		14	Original stucco, brick, floors or ceilings	0	10	15	25	1.00
		15	Original statues or bass-reliefs	0	10	15	25	1.00
		16	Original gable/fronton	0	10	15	25	1.00
		17	Original balconies and railings	0	10	15	25	1.00
		18	Original mosaics or stonework	0	10	15	25	1.00
		19	Original paintings or frescoes	0	10	15	25	1.00
		20	Degradation state of artistic assets	−5	10	15	25	1.00
		21	Authenticity/ originality (global, elements)	0	10	15	25	1.00

(*continued*)

Table 3. (*continued*)

%	Criteria	No	Element	Class				Weight
				A	B	C	D	
		22	Official monument (national, regional, local, protected area) status	0	10	15	25	1.50
		23	Particular construction techniques/materials	0	10	15	25	0.50
		24	Conservation state of original materials	-5	10	15	25	0.50
		25	Representative historical events	0	10	15	25	0.50
		26	Archaeological site	0	10	15	25	1.50
		27	Representative/ original wooden framework	0	10	15	25	1.00
		28	Past restoration work	−5	10	15	25	1.00
10%	URBANISTIC	29	Importance in contouring the street profile	−5	10	15	25	1.50
		30	Importance in contouring the urban silhouette	−5	10	15	25	1.50
		31	Annexes, relation with the urban pattern	0	10	15	25	1.00
		32	Location (central area, touristic area)	0	10	15	25	1.50
		33	Representative/particular shape of the roof	0	10	15	25	1.00
5%	SOCIAL ECONOMIC	34	Public/social functions	0	10	15	25	1.50
		35	Importance for the local community memory	−5	10	15	25	1.00
		36	Economic value	0	10	15	25	1.50
		37	Cultural functions	0	10	15	25	1.50
						$I_{V\ CULT}$		

3.1.1 Results Without Considering the Cultural Value

When the cultural value was not considered, and the original existing methodology of Benedetti and Petrini [12] was followed, together with the adapted mean damage assessment [9], there was obtained the seismic vulnerability assessment of the six churches, from a structural point of view. The vulnerability curve for each church, together with the mean vulnerability curve of all six churches are presented in Fig. 5.

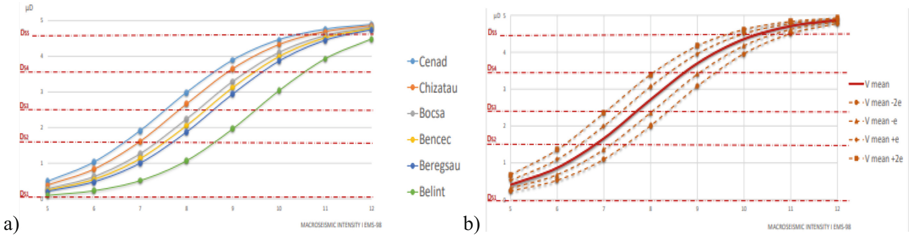


Fig. 5. Only structural assessment: a) Individual vulnerability curves; b) mean vulnerability curve for all six churches.

The results indicate a medium seismic vulnerability for all six churches, in the range of damage states D2-D3 for the probable macroseismic intensities VIII and IX EMS-98. This indicates the possibility of appearance of moderate to severe damages to non-structural elements, but only slight to moderate damages to the structural ones.

3.1.2 Results with the Cultural Value Considered

When the cultural value of the investigated churches is considered, the author's methodology is followed [13], determining the seismic vulnerability influenced by the cultural value. The vulnerability curve for each church, together with the mean vulnerability curve of all six churches are presented in Fig. 6.

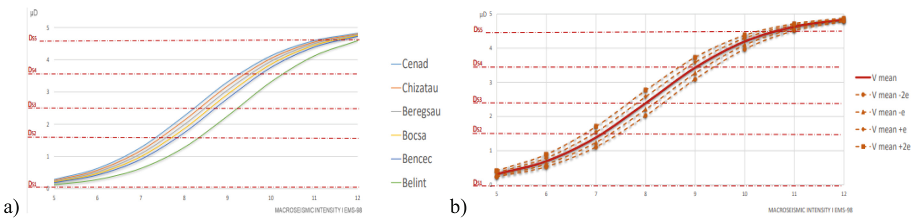


Fig. 6. With cultural value: a) Individual vulnerability curves; b) mean vulnerability curve for all six churches.

The results indicate a slight change of vulnerability in comparison with the assessment without the consideration of the cultural value. The medium seismic vulnerability of all churches decreases by 5% when the cultural value is considered. This happens because the consideration of the cultural value tends to bring all the vulnerability indexes in the same range, as all the investigated buildings are very similar in terms of architectural-artistic, urbanistic and socio-economic values. So, from a structural point of view, there is a higher vulnerability difference between the investigated churches, but from a cultural point of view, all the churches are quite similar in terms of vulnerability, as presented in Fig. 7.

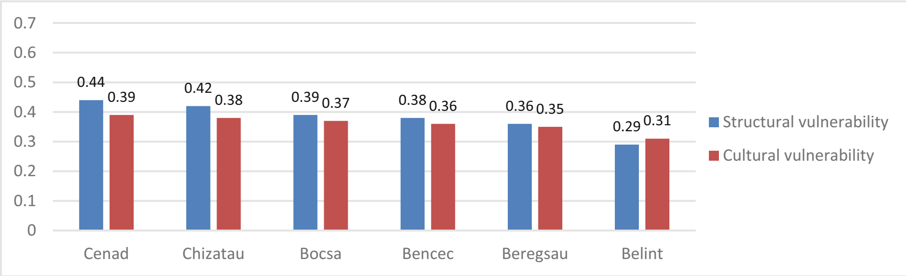


Fig. 7. The results ordered in a top of the most vulnerable churches according to empiric methodology.

3.2 Vulnerability Assessment According to Italian Methodology

According to the Italian Directive 47 of 2011 [14], there can be adopted 3 levels of seismic risk assessment (Levels of Valuation LV1, LV2 and LV3) for cultural heritage, depending on the complexity of the analysis. One of the most common methods is the Level LV1 assessment, which represents a qualitative analysis based on on-site survey, defining the seismic capacity of the structure expressed in terms of PGA, following Eqs. 5, 6 [11].

$$\mathrm{i_v} = \frac{1}{6} \cdot \frac{\sum_{\mathrm{k}=1}^{28} \rho_{\mathrm{k}} \cdot \left(\mathrm{v_{k_i}} - \mathrm{v_{kp}}\right)}{\sum_{\mathrm{k}=1}^{28} \rho_{\mathrm{k}}} + \frac{1}{2} \tag{5}$$

$$\mathrm{a_{LSLS}S} = 0.025 \cdot 1.8^{5.1-3.44\mathrm{i_v}}\left[\mathrm{g}\right] \tag{6}$$

where ρ_k is the the weight of each collapse mechanism considered (0 if not present, or ranging 0,5 -1), v_{ki} is the score assigned for the k-th mechanism related to the evaluated vulnerability and v_{kp} is the score assigned for the k-th mechanism related to the seismic-resistant advice. S is a coefficient depending on subsoil and topographic categories.

Based on this multi-level approach, in Diaz Fuentes [15] and in D'Amato et. Al. [16], there was proposed a simplified level of evaluation, the LV0, which is appropriate for territorial scale evaluation. The LV0 provides a Risk score R, which represents a combination of Hazard H and vulnerability V, following Eqs. 7 [11].

$$\boldsymbol{R} = [H+1] \times V, \boldsymbol{H} = \sum_{k=1}^{7} h_{k,i}, \boldsymbol{V} = \sum_{k=1}^{13} \rho_{k,i} v_{k,i} \tag{7}$$

3.2.1 Results Following LV0 and LV1 Methodology

The results obtained following the LV1 methodology, in terms of global vulnerability index based on the acceleration expected for each church are presented in Table 4. The acceleration factor is calculated by dividing the acceleration obtained by the ground acceleration expected in a date area for the considered limit state.

Table 4. Global vulnerability index for the investigated churches according to LV1 analysis.

Church	**i_v** (global vulnerability index)	**F_C** (confidence factor)	**a_g [g] expected**	**$a_{Og,LSLS}$** [g] - horizontal ground acceleration/F_c in Life-Safety Limit State	**$f_{aO,SLV}$** - horizontal acceleration factor at Life-Safety Limit State	**$a_{Vg,LSLS}S$** [g] - vertical ground acceleration /F_c in Life-Safety Limit State	**$f_{aV,SLV}$** - vertical acceleration factor at Life-Safety Limit State
Holy Spirit Descent Church (CENAD)	0.587	1.35	0.2	0.081	0.405	0.083	0.414
God's Mother Nativity Church (CHIZATAU)	0.566		0.15	0.080	0.534	0.081	0.542
Saint Nicholas Church (BOCSA)	0.460		0.15	0.099	0.661	0.101	0.672
Saint Nicholas Church (BENCECU DE JOS)	0.450		0.2	0.107	0.534	0.109	0.545
Saint George Church (BERGSAU MARE)	0.428		0.2	0.112	0.558	0.114	0.570
Jesus Resurrection Church (BELINT)	0.389		0.15	0.115	0.763	0.116	0.775

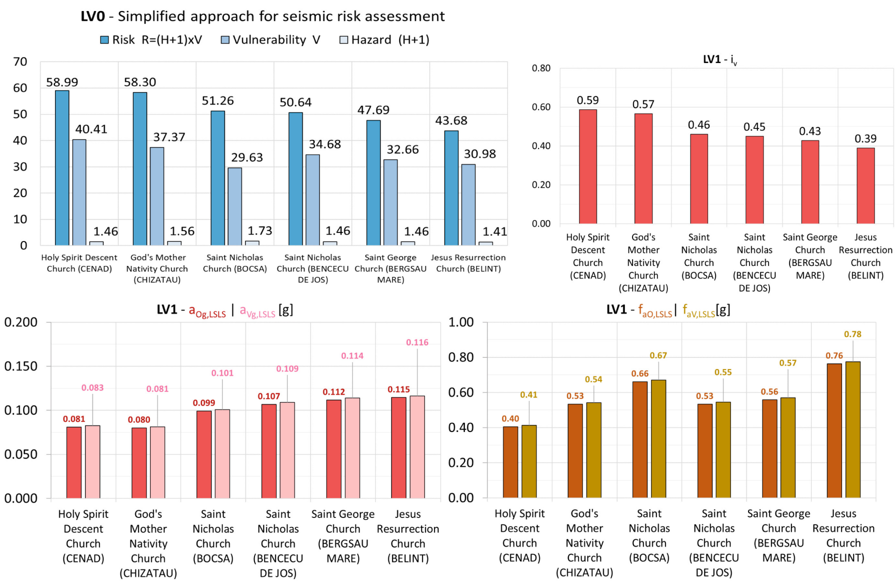


Fig. 8. The results following LV0 and LV1 methodology.

The results obtained following both LV0 and LV1 analysis are presented in Fig. 8, indicating a good correlation between the 2 Levels of Valuation. The results indicate the church of Cenad to be the most vulnerable, while the least vulnerable seems to be the church in Belint. The obtained horizontal acceleration at LSLS is $a_{Og,LSLS} = 0.080$ g ÷ 0.115 g, while the obtained vertical acceleration at LSLS is $a_{Vg,LSLS} = 0.081$ g ÷ 0.116 g. The expected a_g on rock soil ($T_R = 225$ years) is 0.15g for the churches in Chizatau, Belint and Bocsa and 0.20 g for the churches in Cenad, Bencecu de Jos and Beregsau Mare.

4 Conclusion

The comparison of the results obtained following Romanian and Italian procedures indicated a good correlation of the vulnerability classification, all methods indicating the Church in Cenad as the most vulnerable one, followed by the Church in Chizatau, the Church in Bocsa, then the one in Bencec, the Church in Beregsau and the less vulnerable is the Church in Belint. The empiric vulnerability assessment methodology adapted for Banat area, proposed by the Romanian authors tends to underestimate with 15% the seismic vulnerability of the investigated churches. None of the investigated churches satisfies the LSLS verification (Fig. 9).

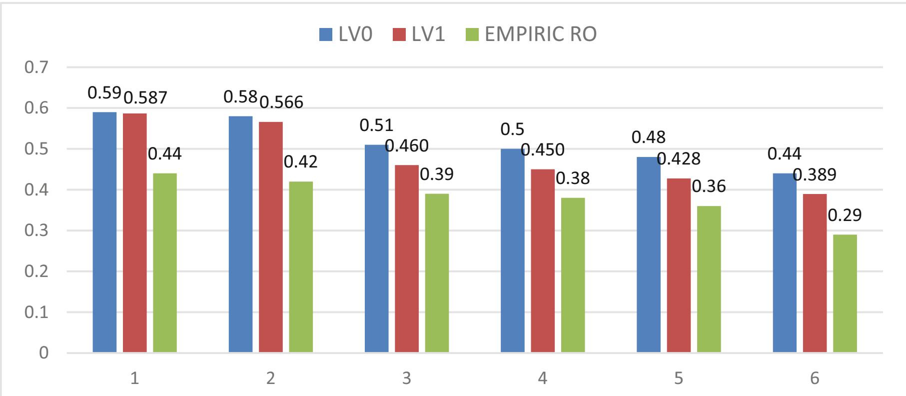


Fig. 9. Comparison of results

References

1. Mosoarca, M., Victor, G.: Structural safety of historical buildings made of reinforced concrete, from Banat region - Romania. J. Cult. Herit. (2013). https://doi.org/10.1016/j.culher.2012.11.015
2. Formisano, A., Vaiano, G., Fabbrocino, F., Milani, G.: Seismic vulnerability of Italian masonry churches: the case of the Nativity of Blessed Virgin Mary in Stellata of Bondeno Seismic vulnerability of Italian masonry churches: The case of the Nativity of Blessed Virgin Mary in Stellata of Bondeno. J. Build. Eng. **20**(July), 179–200 (2018). https://doi.org/10.1016/j.jobe.2018.07.017

3. Clementi, F., Ferrante, A., Giordano, E., Dubois, F., Lenci, S.: Damage assessment of ancient masonry churches stroked by the Central Italy earthquakes of 2016 by the non-smooth contact dynamics method. Bull. Earthq. Eng. **18**(2), 455–486 (2020)
4. Fofiu, M., Mosoarca, M., Onescu, I., Palade, M., Olariu, G., Popovici, T.: Case study of consolidation, rehabilitation, and restoration of the 'Sfantul Filimon' monastery. In: CoHeSion (2021)
5. Mosoarca, M., Gioncu, V.: Failure mechanisms for historical religious buildings in Romanian seismic areas. J. Cult. Herit. **14**, 65–72 (2013)
6. Lo Monaco, A., et al.: Seismic Assessment of Typical Historical Masonry Churches in Banat region, Romania-Part I-NC-ND license (https://creativecommons.org/licenses/by-nc-nd/4.0) Peer-review under responsibility of the scientific committee of the XIX ANIDIS Conference, Seismic Engineering in Italy (2022). www.sciencedirect.com
7. Woessner, J., et al.: The 2013 European Seismic Hazard Model: key components and results. Bull. Earthq. Eng. **13**(12), 3553–3596 (2015). https://doi.org/10.1007/s10518-015-9795-1
8. Ministry of regional development public administration and european funds, Romanian Design Code P100-1/2013. in Romanian (2013) http://www.mdrap.ro/userfiles/reglementari/Domeniul_I/I_22_P100_1_2013.pdf. Accessed 28 Jan 2019.
9. Mosoarca, M., Onescu, I., Onescu, E., Anastasiadis, A.: Seismic vulnerability assessment methodology for historic masonry buildings in the near-field areas. Eng. Fail. Anal. (2020)
10. Onescu, E., Onescu, I., Mosoarca, A.M.: Seismic vulnerability assessment methodology for historical buildings with cultural value", SAHC congress, Volume Vulnerability and risk analysis (2021)
11. Lo Monaco, A., et al.: Seismic assessment of typical historical masonry churches in the Banat region, Romania-Part II-NC-ND license (https://creativecommons.org/licenses/by-nc-nd/4.0) Peer-review under responsibility of the scientific committee of the XIX ANIDIS Conference, Seismic Engineering in Italy (2022). www.sciencedirect.com
12. Benedetti, D., Petrini, V.: On the seismic vulnerability of masonry buildings: an evaluation method (in Italian). L'Industria delle Costruzioni **149**, 66–74 (1984)
13. Apostol, I.: Seismic vulnerability assessment of historical urban centres, Ph.D., Politehnica Timisoara
14. G.U. n. 47., February 26, 2011. Directive of the Prime Minister dated on 09/ 02/2011. Assessment and mitigation of seismic risk of cultural heritage with reference to the technical code for the design of construction, issued by D. M. 14/ 01/2008.
15. Andrea, D., Fuentes, D.: Diseño de herramientas de evaluación del riesgo para la conservación del patrimonio cultural inmueble. México, Publicaciones ENCRyMINAH, Aplicación en dos casos de estudio del norte andino chileno. In (2016)
16. D'Amato, M., Laterza, M., Diaz Fuentes, D.: Simplified seismic analyses of ancient churches in matera's landscape. Int. J. Architect. Heritage **14**(1), 119–138 (2020). https://doi.org/10.1080/15583058.2018.1511000