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OPTIMIZATION OF EMPIRICAL SEISMIC VULNERABILITY ASSESSMENT FOR MASONRY BUILDINGS FOLLOWING NONLINEAR ANALYSIS

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Abstract

Timisoara is the most important city located in Banat seismic area, characterized by shallow earthquakes of crustal type and was selected to be European Capital of Culture 2021. The majority of the historical buildings are made in masonry, with masonry vaults and wooden floors.
First part of the paper presents a quick and simplified empirical methodology based on European studies. The second part presents a detailed mechanical nonlinear analysis obtained for some of the most important historical buildings in Timisoara, based on complete survey and site inspection. Moreover, the authors present a direct correlation between the empirical and the mechanical seismic vulnerabilities. In the end, based on the correlation results, there is presented the proposed empirical seismic vulnerability assessment methodology for the near-field events. The methodology considers the specific failure mechanism for buildings with same characteristics and the particularities of Banat seismic area.
The proposed methodology aims to adapt the quick and simplified empirical methodology to the near-field earthquakes effects. This could serve for quick and simplified assessment of seismic vulnerability for any building with similar mechanical, geometrical, architectural and urbanistic characteristics as the case study buildings, in areas with earthquakes similar to those specific to Banat seismic area. This kind of study could provide a better knowledge for the local authorities, helping them to develop or improve earthquake mitigation plan and to define new earthquake engineering design recommendations.

Keywords: masonry, earthquake, vulnerability assessment, history, nonlinear analysis

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1 INTRODUCTION

1.1 Case study area

Seismic vulnerability assessment represents an interdisciplinary task than can offer valuable tools for the risk reduction policies at a municipal level. The lack of seismic design rules at the moment of design or the lack of proper consolidation work during the lifetime of the buildings has led to an increase in the seismic risk of historic urban centers. The seismic risk can be divided into the sum of three elements, such as hazard, vulnerability, and exposure [1]. This paper aims to evaluate the seismic vulnerability of some historical masonry building and adapt an existing European vulnerability assessment methodology to the particularities of the site.

The Banat region represents an important area located in the western part of Romania. The biggest city in the Banat region is Timisoara, that was first recognized in 1177 as the "Fortress of Timis," after the main nearby river [2]. After several administrations, such as Ottoman, Habsburgic, and Austro-Hungarian, the city developed into an important commercial and defensive pole, presenting a bastionary fortification system in Vauban architectural style, as shown in Figure 1 [2].

Figure 1: The bastionary fortification system for Timisoara city [2]

The most important historical area of the town is the Cetate district, located in the interior contour of the fortification, followed by two other districts, Iosefin and Fabric, which appeared outside the defensive walls, as presented in Figure 2 [3].

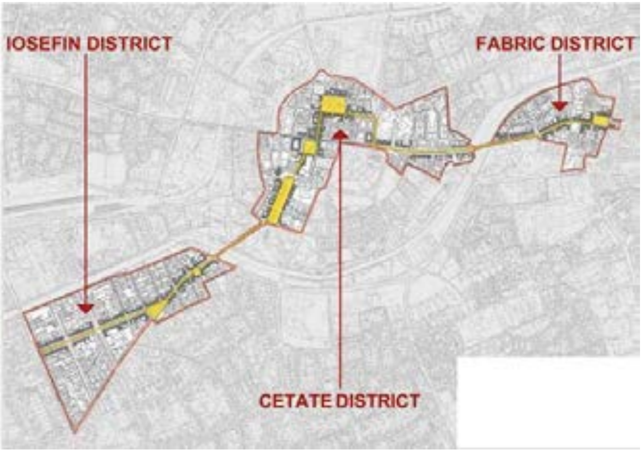

Figure 2: The three historic districts of Timisoara city [3]

The case study area in this paper is Fabric historic district, which appeared at first as a residential area for the craftsman. The streets are both rectangular and organic, with widths between 10 and 16 meters, and the buildings are made in masonry. Despite the industrial aspect of the area, the existing succession of public squares increases the quality of life in the area. An image from 1901 with the character of the district is illustrated in Figure 3 [2].

Figure 3: The spirit of Fabric district in 1901 [2]

1.2 Seismicity of the area

The determination of the seismic hazard for a specific area represents a difficult task, than can be achieved through both probabilistic and deterministic methods. At a global level, there was made a seismic hazard map, as presented in Figure 4 [4].

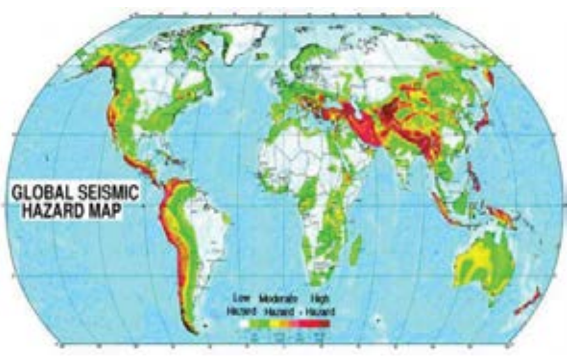

Figure 4: Seismic hazard map at a global level [4]

In Romania, there are two seismic areas, Vrancea and Banat. Vrancea is the most important seismic region, characterized by strong earthquakes with magnitudes around $M_w = 7.0$ of intermediate depth. Less dangerous earthquakes characterize the Banat region, with magnitudes around $M_w = 5.6$ of crustal type, with focal depths between 1 and 35 km [5]. The general seismicity of Romania, faults, and past seismic events is presented in Figure 5 [6].

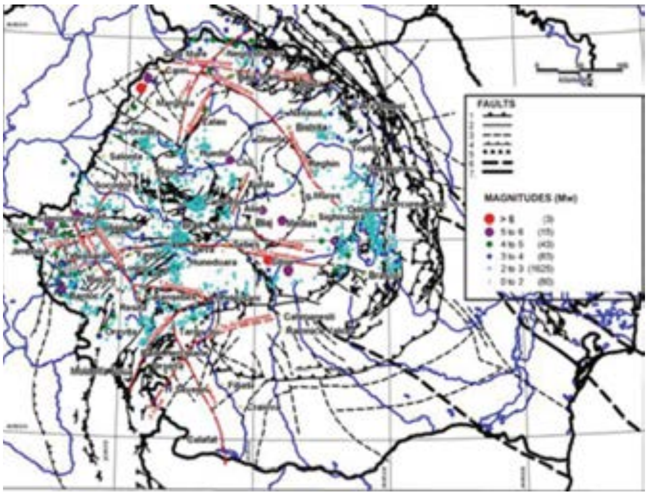

Figure 5: The location of the seismic faults and past earthquakes in Romania [6]

In Timisoara city, there are two active seismic faults located at less than 10 km from the city center, as shown in Figure 6 [3].

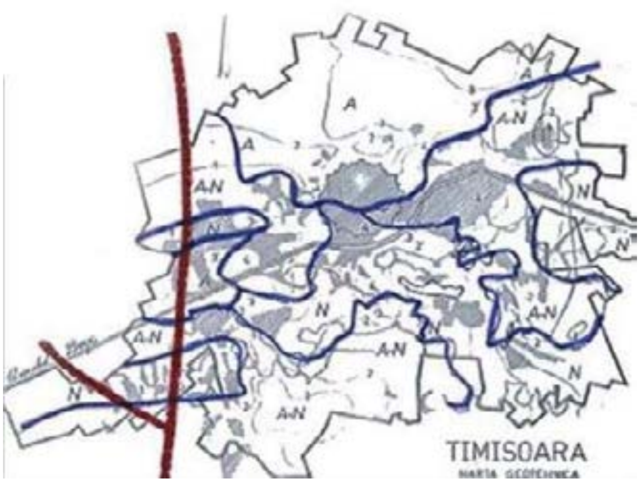

Figure 6: The location of the two active seismic faults in Timisoara [3]

The strongest seismic event registered in Banat area was the earthquake from 1991, in Banloc city, at less than 40 km from Timisoara, with a magnitude $M_w = 5.5$ and a focal depth of 11 km, followed by a strong aftershock of a magnitude $M_w = 5.3$ and a focal depth of 5 km [7]. After the event, there were registered damages, especially to attics, arches, lintels, and chimneys, as presented in Figure 7 [3],[8].

Figure 7: Damages to masonry buildings in the epicenter after Banloc earthquake, 1991 [3], [8]

There were observed both in-plane and out-of-plane failure mechanisms. The in-plane mechanism that can be noticed is mostly the diagonal shear cracking, especially in the façade masonry walls. Also, the vertical cracks can be seen due to the presence of strong vertical forces and L and R surface waves. Following the on-site observation, there was defined a specific failure mechanism for historic masonry buildings located in the near-field areas, after earthquakes of crustal type, as illustrated in Figure 8 [9].

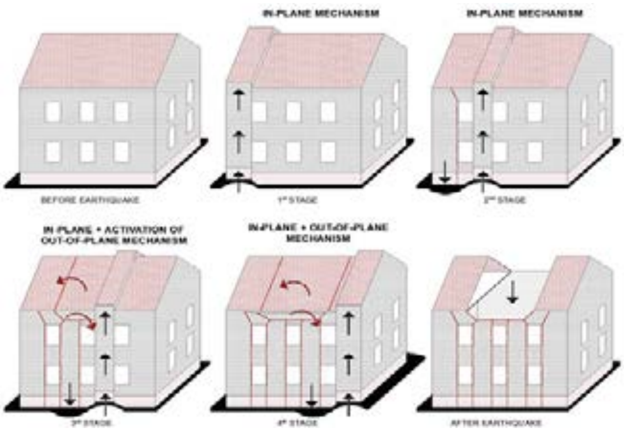

Figure 8: The specific failure mechanism for historic masonry buildings in the near-field areas similar to Banloc seismic region [9]

When the real observed damages were compared with the EMS-98 damage scale for masonry buildings [10], there was noticed the fact that the real damage was around damage state D2-D3, as shown in Figure 9 [9].

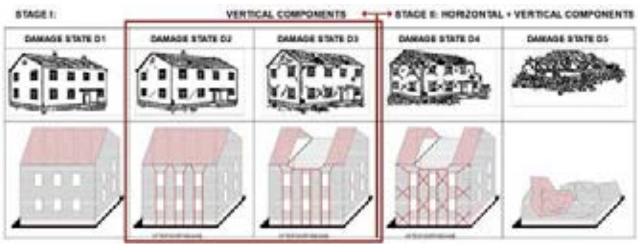

Figure 9: Correlation between EMS-98 damage scale and real damage observed after Banloc earthquake, 1991 [9]

For Timisoara city, there can be generated an expected damage scenario, similar to the one that occurred in Banloc area. The peak ground acceleration for Timisoara is considered to be 0.20g after the Romanian design code [11]. Following a simplified correlation law presented in Equation (1), there was determined that the most probable macroseismic intensity for the area is IX EMS-98, as shown in Figure 10 [12].

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

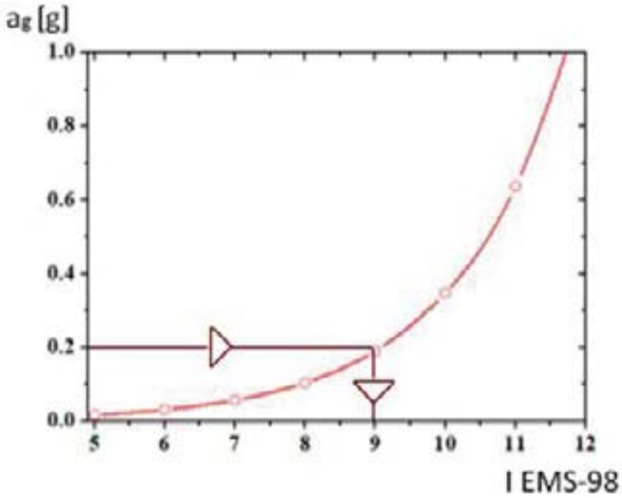

Figure 10: Correlation between EMS-98 damage scale and real damage observed after Banloc earthquake, 1991 [12]

1.3 Case study buildings

The investigated buildings are considered to be representative of the area, from all existing height regimes. Their location is presented in Figure 11 [13].

Figure 11: Location of the case study buildings [13]

In the area, there can be noticed that almost all buildings present the basement, while the minimum height regime is basement and ground floor, and the biggest is a basement, ground floor and two levels. The structural system of all investigated buildings is the masonry of burnt clay brick and lime. The buildings are located with the longest dimension along the main street, presenting massive façade and intermediate walls with thicknesses from 80 centimeters in the basement and 40 centimeters on the last floor. The transversal walls are not connected with the façade walls in most of the cases and are much thinner, around 15 centimeters [3], [14].

The horizontal structural systems are masonry vaults above the basement and sometimes ground floor and wooden floors for the other levels. There can be noticed, in many cases, a very tall complex wooden framework for the roof structure [3], [14].

The six selected buildings for investigation are presented in Figure 12 [13].

Figure 12: The six selected buildings for further investigation [13]

2 EMPIRICAL SEISMIC VULNERABILITY ASSESSMENT

2.1 Description of the existing methodology

The empirical methodologies represent a useful tool for a quick and simplified seismic vulnerability assessment that can also be applied at an urban scale [15].

The existing methodology that is used in this paper was proposed at first by Benedetti and Petrini [16] and was later developed by Mazzolani and Formisano [17].

The procedure is simple, based on visual inspection that leads to the fulfillment of an investigation form (Fig. 13), in which for several parameters, there is assigned a score for each possible situation. The parameters are in a number of 10 when the building is considered as isolated structural unit and 15 when there is also considered the influence of the adjacent buildings from the aggregate. For each parameter, there is also assigned a weight that illustrates its importance. All parameters and their associated weight are used following the existing Italian methodology [17]. The vulnerability index represents the sum of each parameter, whit the class score and weight assigned, following Equation (2) [9].

$$I_V = \sum s_i \times w_i \tag{2}$$

No	Factor	Class				Weight
		A	B	C	D	
1	Organization of vertical structures	0	5	20	45	1
2	Nature of vertical structures	0	5	25	45	0.25
3	Location of the building and type of foundation	0	5	25	45	0.75
4	Distribution of plan resisting elements	0	5	25	45	1.5
5	Plain regularity	0	5	25	45	0.5
6	Vertical regularity	0	5	25	45	1
7	Type of floors	0	5	15	45	1
8	Roofing	0	15	25	45	0.75
9	Details	0	0	25	45	0.25
10	Physical conditions	0	5	25	45	1
11	Presence of adjacent buildings with different height	-20	0	15	45	1
12	Position of the buildings in the aggregate	-45	-25	-15	0	1.5
13	Presence and number of staggered floors	0	15	25	45	0.5
14	Effect of either structural or typological heterogeneity among adjacent structural unit	-15	-10	0	45	1.2
15	Percentage difference of opening area among adjacent facade	-20	0	25	45	1

Figure 13: Empirical vulnerability form [9]

After the determination of the vulnerability index, the index is normalized in the range of 0÷1, following Equation (3) [9].

$$V = (I_V - I_{V\,MIN}) / (I_{V\,MAX} - I_{V\,MIN}) \quad (3)$$

The last step in the process of determination of the empirical seismic vulnerability is the damage estimation, where following the normalized vulnerability index, there can be estimated the mean damage grade and the expected damage state, following Equation (4). The correlation between the mean damage grade and expected damage level is illustrated in Figure 14 [18].

$$\mu_D = 2.5\{1 + \tanh[(I + 6.25V - 13.1)/\Phi]\} \quad (4),$$

where I represents the macroseismic intensity, V is the normalized vulnerability index and Φ is the factor that modifies the vulnerability curve slope and is considered equal to 2.3 for residential buildings [19].

μ_D	Damage state	Most probable degradation level
0.0-1.5	D1	Slight (no structural damage, slight non-structural damage)
1.5-2.5	D2	Moderate (slight structural damage, moderate non-structural damage)
2.5-3.5	D3	Substantial to heavy (moderate structural damage, heavy non-structural damage)
3.5-4.5	D4	Very heavy (heavy structural damage, very heavy non-structural damage)
4.5-5.0	D5	Destruction (very heavy structural damage)

Figure 14: Correlation between mean damage grade and expected level of damage [18]

2.2 Results of the applied existing methodology

The application of the empirical seismic vulnerability has led to a series of vulnerability indexes for ten and 15 parameters, as presented in Table 1.

Building	I_{V10}	I_{V15}
1	68.75	98.75
2	108.75	110.25
3	98.75	61.25
4	93.75	118.75
5	113.75	66.75
6	130	160

Table 1. Vulnerability indexes for the six investigated buildings

Following the determined vulnerability indexes, there were also designed the vulnerability curves, as presented in Figure 15 for buildings considered as isolated and in Figure 16 for buildings considered in aggregate. The comparison between the mean vulnerability curves for both situations is illustrated in Figure 17.

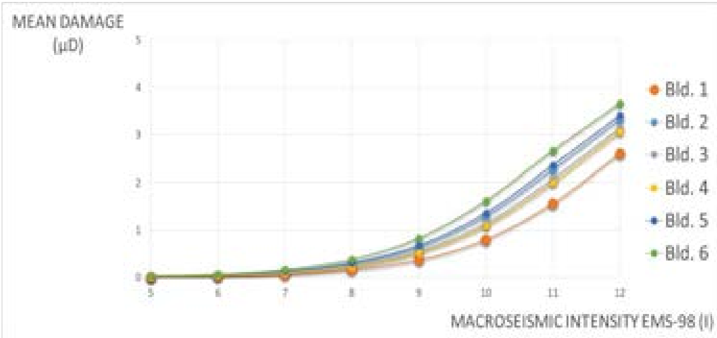

Figure 15: Empirical vulnerability curve for the six investigated buildings considered as isolated structural units

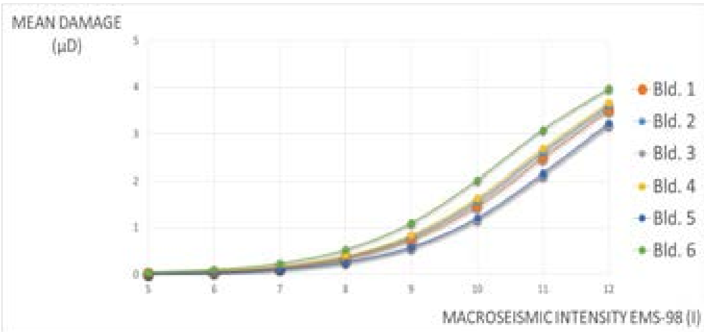

Figure 16: Empirical vulnerability curve for the six investigated buildings considered in aggregate

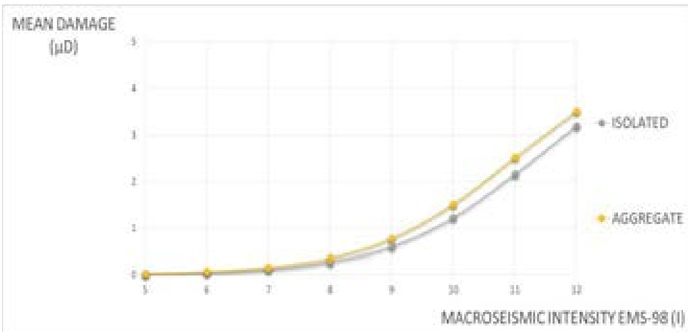

Figure 17: Comparison between mean vulnerability curves for both isolated and aggregate situations

The results illustrate a low vulnerability for a macroseismic intensity IX EMS-98, according to the most probable seismic scenario, in the range of damage state D1 for both situations, which means no expected damages.

Considering the real damages observed in Banloc in a similar situation, in the ranges of D2-D3, there is highlighted the need for performing nonlinear analysis to adapt the empirical methodology for near-field effect.

3 MECHANICAL SEISMIC VULNERABILITY ASSESSMENT

3.1 Nonlinear analysis

The numerical analysis represents a more precise tool in the process of seismic vulnerability assessment, indicating the weakest points of the structure [20].

The pushover analysis was obtained with Tremuri software and investigated the in-plane failure mechanism for the six investigated buildings, considered as isolated structural units. There was used the local seismic spectrum for Banat region, as illustrated in Figure 18 [21] while the mechanical proprieties for the masonry structures were determined following experimental tests and other technical expertise for similar buildings, as illustrated in Table 2 [3].

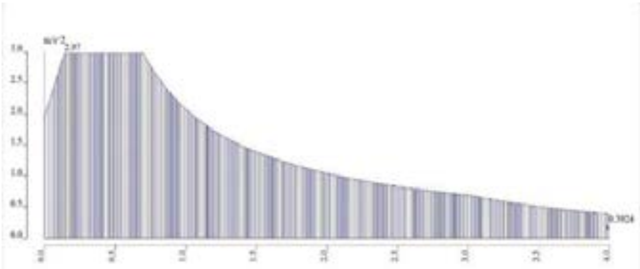

Figure 18: The local spectrum for Banat seismic region [21]

	fk [N/mm²]	fvk0 [N/mm²]	E [N/mm²]	G [N/mm²]	Density [kg/m³]
URM	2.35	0.06	2350	940	1800

Table 2. Mechanical proprieties for the masonry structures

The analysis made with Tremuri is a simplified analysis, appropriate for the investigation of more than one building, and can be used for historical masonry buildings. It has revealed the expected cracks damage distribution, as presented in Figure 19 [13].

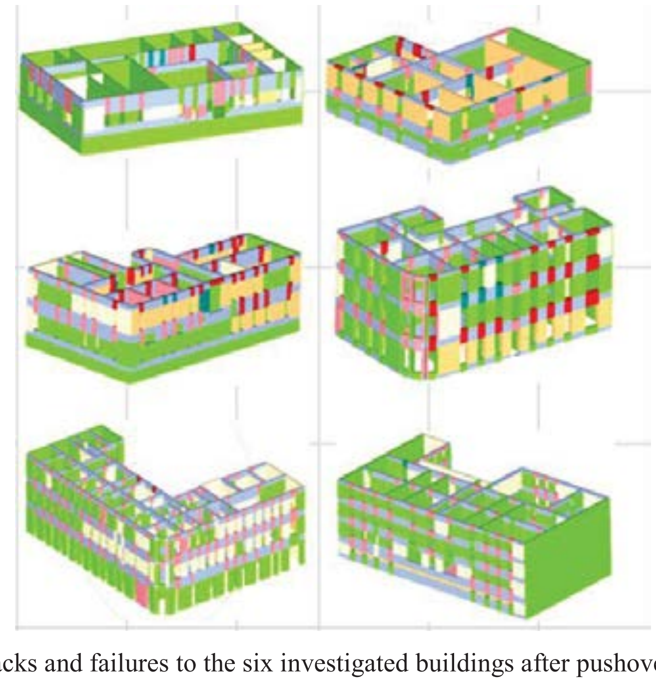

Figure 19: Cracks and failures to the six investigated buildings after pushover analysis [13]

The pushover analysis has revealed that the buildings would suffer both nonstructural and structural damages for the considered seismic scenario, around damage states D2-D3. In Table 3, there are presented the yielding and ultimate displacement and also the maximum shear forces [13].

Bld. No.	Yielding displacement Δy [cm]	Maximum shear force V [kN]	Ultimate displacement Δu [cm]	Interstorey drift [%]
1	0.08	3482	0.28	0.040
2	0.14	966	0.62	0.107
3	0.04	4006	0.12	0.113
4	0.79	2735	2.84	0.318
5	0.60	5309	1.74	0.160
6	0.54	15096	1.74	0.220

Table 3. Displacements, shear forces and interstorey drift for the six investigated buildings [13]

According to the interstorey drift values, there can also be estimated the most probable damage state for each investigated building, following Table 4 [13].

URM	Damage state D2	Damage state D3	Damage state D4	Damage state D5
	ID < 0.1%	0.1%<ID<0.3%	0.3%<ID<0.6%	0.6%<ID

Table 4. Correlation between interstorey drift values and most probable damage state [13]

3.2 Conclusion of the numerical analysis

The results indicated by the pushover analysis highlight the possibility of an appearance of cracks and failures due to bending forces, especially to the lintels at the upper part of the buildings. Also, there can be noticed, in some cases, cracks and failures due to shear forces at the spandrels also located on the top floors. These aspects indicate a general damage state of D2-D3 for all six investigated buildings.

Also, the investigation of the interstorey drift values indicates the same damage states D2-D3 for all six investigated buildings.

The two aspects previously presented suggest that the existing empirical seismic vulnerability assessment methodology tends to underestimate the real vulnerability of historic masonry buildings located in the near-field areas.

In this case, an adaptation is necessary to be able to provide precise and quick results at an urban scale for similar buildings located in seismic regions with characteristics similar to Banloc region.

Because the existing methodology is well-used at the European scale, there is proposed to keep it in the original form and modify only the damage estimation formula.

4 NEW PROPOSED EMPIRICAL METHDOLOGY FOLLOWING NONLINEAR ANALYSIS

4.1 New proposed damage estimation formula

The investigation of real damages after past earthquakes in similar areas and on similar buildings have illustrated considerable damages to structural elements, without affecting the bearing capacity of the structure, so a damage state of D2-D3.

The same probable damage state was indicated by the nonlinear analysis obtained with Tremuri software and also, by the investigation of the interstorey drift values obtained following the pushover analysis.

Both visual and numerical investigation revealed the fact that, for a macroseismic intensity of IX EMS-98, there is the need to adapt the damage estimation formula.

This adaptation could provide the necessary tools for correctly assessing the seismic vulnerability of historic masonry buildings in the near-field areas, similar to Banloc region, in a quick and simplified way.

The first part of the methodology, regarding the fulfillment of the vulnerability form and determination of the vulnerability index and implicitly the normalized vulnerability index, are proposed to remain precisely in the original structure. There is recommended to modify just one parameter from the damage distribution formula (Equation 4), the parameter that influences the slope of the vulnerability curve. The new proposed damage estimation formula is presented in Equation (5) [13].

$$\mu_D = 2.5\{1 + \tanh[(I + 12.5V - 13.1)/\Phi]\} \qquad (5),$$

where I represents the macroseismic intensity, V is the normalized vulnerability index and Φ represents the parameter of the curve's slope, equal with 2.3 for residential buildings.

4.2 New vulnerability curves following the proposed damage estimation formula

Following the new proposed damage estimation formula, there were redesigned the vulnerability curves for the six investigated buildings, as illustrated in Figure 20 and Figure 21.

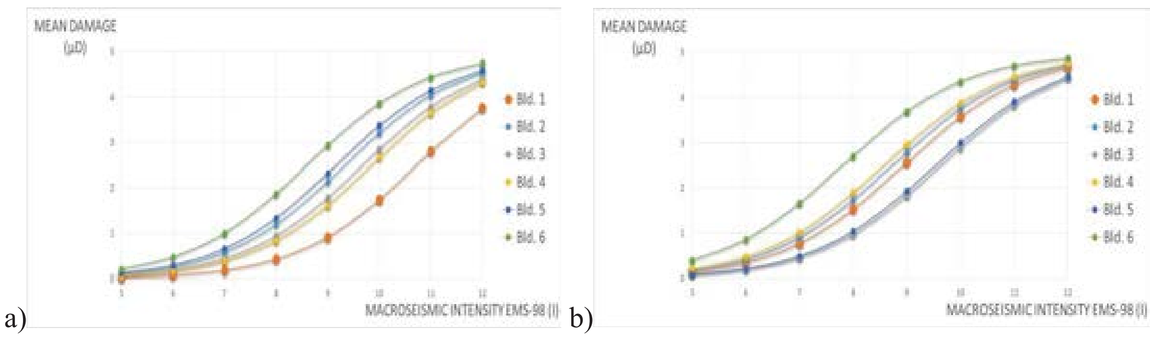

Figure 20: New empirical vulnerability curve for the six investigated buildings after proposed damage estimation formula considered: a) as isolated structural units; b) in aggregate condition

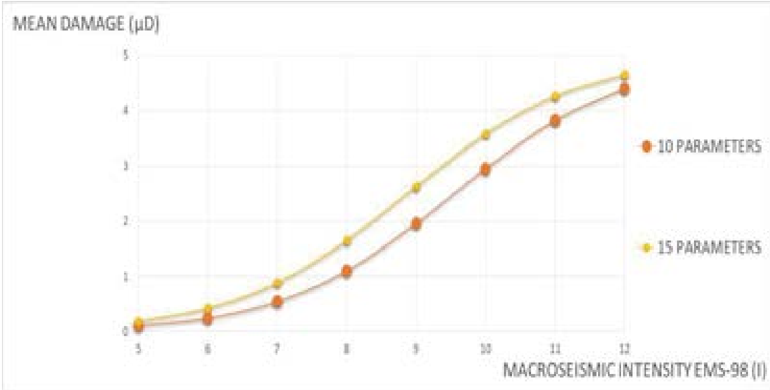

Figure 21: New comparison between mean vulnerability curves for both isolated and aggregate situations, following proposed damage estimation formula

5 CONCLUSION

The new results are in accordance with the real damages observed after the Banloc earthquake from 1991 and also with the results of the numerical analysis.

This aspect indicates the fact that the proposed damage estimation formula is appropriate for assessing the seismic vulnerability for historic masonry buildings located in the near-field areas similar to Banloc seismic region.

The most probable damage states of D2-D3 indicates a medium vulnerability for the investigated buildings that can be dangerous for the historic areas of Timisoara city. There is a high possibility of having significant damages to nonstructural elements and moderate damages to structural ones, but without affecting the bearing capacity of the structures. Because all the buildings are in protected areas, there is highlighted the possibility of losing irreplaceable cultural, architectural-artistic and urbanistic valuable elements.

The new proposed damage estimation formula could help provide quick and accurate vulnerability curves for historic masonry building with similar characteristics to the ones in Timisoara city, that are located in seismic regions with the same proprieties with Banloc area.

REFERENCES

[1] A. Formisano, *Expected Seismic Risk in a District of the Sant'antimo's Historical Centre*, Trends in Civil Engineering and its Architecture, vol. 2, no. 1, 2018.

[2] M. Opris, *Timisoara - mica monografie urbanistica*, In Romania. Bucuresti: Editura Tehnica, 1987.

[3] M. Mosoarca, I. Onescu, E. Onescu, B. Azap, N. Chieffo, and M. Szitar-Sirbu, *Seismic vulnerability assessment for the historical areas of the Timisoara city, Romania*, Engineering Failure Analysis, vol. 101, pp. 86–112, Jul. 2019.

[4] J. Oluwatobi et al., *Review of world earthquakes*, International Journal of Civil Engineering and technology, vol. 9, issue 9, pp. 440-464, 2018.

[5] E. Oros and M. Diaconescu, *Recent vs. historical seismicity analysis for Banat seismic region (western part of Romania),* Mathematical Modelling in Civil Engineering, vol. 11, no. 1, pp. 1–10, 2015.

[6] A. Bala and V. Raileanu, *Crustal seismicity and active fault systems in Romania*, International Multidisciplinary Scientific GeoConference Surveying Geology and Mining Ecology Management, SGEM, vol. 3, no. 1, pp. 799–806, 2015.

[7] E. Oros, *Macroseismic and instrumental seismicity of the Banat Region and its significance on the local seismic hazard and risk*, in Proc. and CD-Rom of the "Thirty Years from the Romania Earthquake of March 4, 1977" Symposium, 2007.

[8] IPROTIM, *Banloc earthquake report*, unpublished, 1992.

[9] M. Mosoarca, I. Onescu, E. Onescu, and A. Anastasiadis, *Seismic vulnerability assessment methodology for historic masonry buildings in the near-field areas*, Engineering Failure Analysis, 2020.

[10] R. P. Borg, M. Indirli, T. Rossetto, and L. A. Kouris, *L'Aquila earthquake April 6th, 2009: the damage assessment methodologies*, in COST Action C26 "Urban Habitat Constructions Under Catastrophic Events," 2010.

[11] Ministry of regional development public administration and european funds, *Romanian Design Code P100-1/2013*, in Romanian, 2013.

[12] N. Chieffo and A. Formisano, *The Influence of Geo-Hazard Effects on the Physical Vulnerability Assessment of the Built Heritage: An Application in a District of Naples,* Buildings, vol. 9, no. 1, p. 26, 2019.

[13] I. Apostol, *Seismic vulnerability of historical centers*, Ph.D. Thesis, Polytechnic University of Timisoara, 2020, unpublished

[14] I. Apostol et al., *Solutions for improving seismic vulnerability of historic masonry buildings*, in Modern Technologies for the 3rd Millennium, 2018, pp. 131–136.

[15] G. Calvi, R. Pinho, G. Magenes, J. Bommer, L. Restrepo, and H. Crowley, *Development of Seismic Vulnerability Assessment Methodologies over the Past 30 Years*, ISET Journal of Earthquake Technology, vol. 43, no. 472, pp. 75–104, 2006.

[16] D. Benedetti and V. Petrini, *On the seismic vulnerability of masonry buildings: an evaluation method* (in Italian), L'Industria delle Costruzioni, vol. 149, pp. 66–74, 1984.

[17] A. Formisano, R. Landolfo, F. Mazzolani, and G. Florio, *A quick methodology for seismic vulnerability assessment of historical masonry aggregates*, COST Action C26: Urban Habitat Constructions under Catastrophic Events, no. September, 2010.

[18] B. Azap, I. Apostol, M. Mosoarca, N. Chieffo, and A. Formisano, *Seismic vulnerability scenarios for historical areas of Timisoara*, in Modern Technologies for the 3rd Millennium, 2018, pp. 149–154.

[19] R. Vicente, S. Parodi, S. Lagomarsino, H. Varum, J. A. R. Mendes, and D. Silva, *Seismic vulnerability assessment, damage scenarios and loss estimation. Case study of the old city centre of Coimbra, Portugal*, in The 14th World Conference on Earthquake Engineering, 2008.

[20] R. Maio, *Seismic Vulnerability Assessment of Old Building Aggregates*, Universidade de Aveiro, 2013.

[21] A. I. Keller, *Complex assessment of historical wooden framework*, Ph.D. Thesis, Polytechnic University of Timisoara, 2020, unpublished.

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