SEISMIC VULNERABILITY ASSESSMENT OF HISTORICAL URBAN CENTERS

PhD Thesis – Summary

For obtaining the scientific title of doctor at the
Polytechnic University of Timișoara
In the doctoral field of Civil Engineering and Installations

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The PhD thesis „ Seismic vulnerability assessment of historical urban centers" deals with the subject of the vulnerability of the historically built fund to natural hazards, bringing solutions for quick and simplified assessment and proposals for reducing seismic risk.

Why this subject? Natural disasters represent an important aspect of the life of people who live in exposed areas. Heritage, understood by the sum of its tangible and intangible elements, is the basis of authenticity, integrity and the 'spirit of the place', so its conservation is very important. Seismic vulnerability and cultural value represent both contemporary subjects, and the correlation of those two highlights a subject that is debated at large scale in international peer-reviewed journals and renowned conferences.

What stands out in this thesis? The research was carried out over a period of five years, carrying out on-site investigations in over 100 buildings with heritage value, respectively complete surveys and non-linear pushover analyzes for 25 of them. It combines different methodologies validated at European level to propose a simplified methodology for assessing seismic vulnerability in the Banat seismic area, adapted for shallow earthquakes. Moreover, it harmoniously intertwines the field of civil engineering with that of architecture, bringing to the fore for the first time the cultural component within the seismic risk reduction policies. Last but not least, the thesis provides valuable information on the specific failure mechanism of typologies of historic buildings in Timisoara and opens future directions of research of great interest, all information being disseminated in multiple scientific papers and participation in international conferences.

The thesis is structured in 6 chapters, from general to particular and comes with 3 appendices. The chapters refer to an introduction in the subject of the thesis, to a presentation of the seismic evaluation methodologies currently existing in the literature, to the multicriterial analysis of the investigated area, as well as to the impact of cultural value on seismic vulnerability. In chapter five, the results obtained are extrapolated to determine the type and method of failure specific to masonry buildings in the seismic area Banat, following that at the end of the thesis to present the general conclusions, personal contributions and future research directions.

In the first chapter, an introduction to the thesis is made. The area chosen for research includes 105 historic buildings in the Iosefin and Fabric neighborhoods of Timisoara. The selected methodologies are widely used at European level, but are not customized for near-field zones. Thus, the thesis adapts an existing methodology to the particularities of the Banat seismic area through the non-linear analysis performed on 25 buildings, respectively by comparing with the damages observed in the past after the Banloc earthquake. Moreover, the evaluation methodology also takes into account the cultural value of the buildings. Why this? Because, for example, if there are funds for the rehabilitation of 50 buildings, the proposed methodology helps to create a prioritization list so as to ensure the integrity of heritage buildings in the first place, depending on the current level of conservation. In fact, this methodology is one of the pillars needed for an integrated conservation policy.

As main objectives, the thesis aims to come up with a simplified methodology that takes into account the cultural value and can be easily applied at urban level, to define seismic scenarios and specific vulnerability curves for Timisoara, to assess possible losses and to synthesize results obtained by mechanical analysis defining the capacity and fragility curves specific to the masonry buildings in Timisoara.

In the second chapter, a state-of-the-art is made, highlighting the fact that existing methodologies can be classified as empirical, mechanical or hybrid. All methodologies aim to assess the probable level of damage, according to the classification illustrated in Fig. 1 [1].

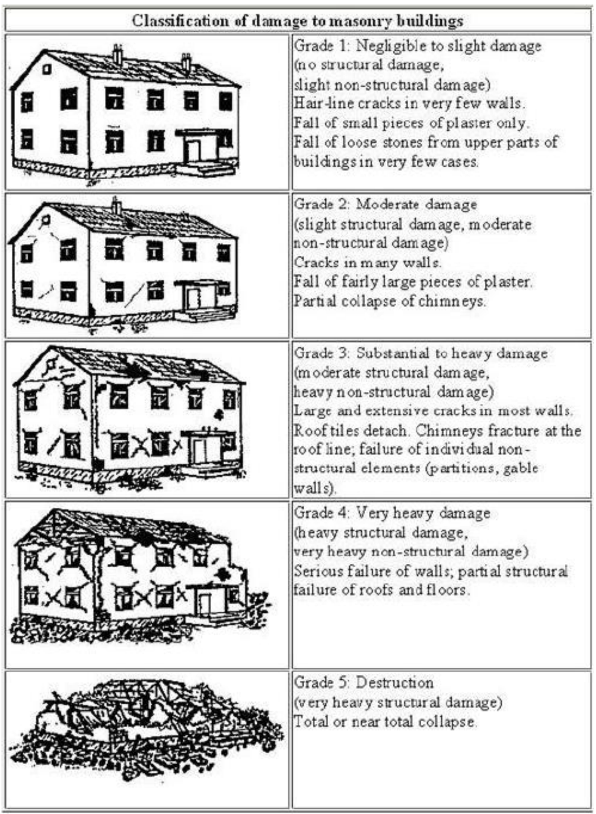


Figure 1. Damage distribution for masonry buildings [1]

The empirical ones are based on a visual assessment to generate a vulnerability score, without the need for much knowledge, and are suitable for a quick preliminary study at the urban level. Among the empirical methodologies, the most frequently used are the “probable damage matrix” [2], the “vulnerability index method” [3], [4], respectively the “method of continuous vulnerability curves” [5].

The mechanical ones are more precise, they need a complete survey and a non-linear analysis software, Tremuri in our case. It offers detailed information on failure mechanism, but is suitable for small groups of buildings. Among the best known, we note the "method of analytically derived vulnerability curves" [6] used in the RISK-EU research project [7], "method based on yield mechanisms" [8], respectively "method based on spectrum capacity ”[9] widely used in the HAZUS or HAZARD US research project [10].

To combine the advantages of the previous two methods, hybrid methods can be used, which make a preliminary analysis with an empirical procedure, then calibrate them based on a mechanical analysis obtained on a small group of buildings and extrapolate results to adapt the initial empirical methodology [11]. They can be widely used and have the advantage of being customized for the investigated area.

Regardless of the chosen methodology, it is recommended to complete the data obtained with data from technical expertise. The proposed methodologies represent a quick alternative, when there is no time or no funds for such expertise.

Also in this chapter are discussed the methodologies for assessing cultural vulnerability, which exist worldwide, but which focus on the possibility of physical loss of some architectural-artistic elements, depending on reaching certain limit states (Fig. 2) [12]. Among the research projects aimed at assessing cultural vulnerability, the European projects PERPETUATE [13] or NIKER [14] stand out. The present thesis develops these methodologies so as to be considered aspects such as heritage, urban, cultural or socio-economic value, in accordance with the principles of Icomos and Iscarsah. This aspect is important for ensuring urban policies of awareness, prevention, response and recovery in case of earthquake.

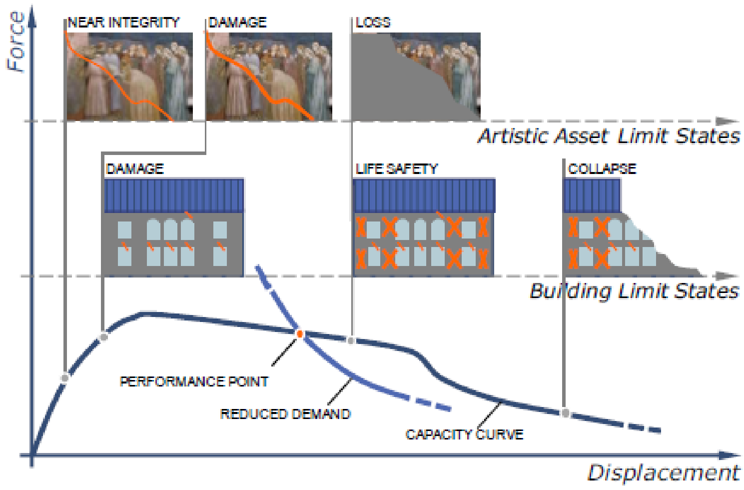


Figure 2. Performance levels and specific limit states for damaging architectural architectural elements according to the PERPETUATE research project [12]

In order to reduce the seismic risk, aspects such as exposure level, vulnerability, respectively hazard must be identified and treated. Hazard is the most difficult to predict or influence, but the other two components can be improved by human action [15].

Chapter three already represents the actual analysis of the 105 historic brick masonry buildings in Iosefin and Fabric and begins with a historical and urban analysis. The two chosen districts were initially built at a distance of 949 meters from the Vauban-style fortress for strategic reasons, later unifying with the city center through constructions dating from more recent periods [16].

By overlapping the maps with the most important historical buildings, the main points of attraction, as well as the possible spaces for organizing outdoor cultural events, according to the Timisoara project European Capital of Culture 2021 [17], a cultural-historical promenade was outlined, as is observed in Fig. 3 [18]. The doctoral thesis studies exactly the buildings that are located along this promenade, a total of 105, of which 68 are located in Iosefin and 37 in Fabric (Fig. 4). The Cetate neighborhood was not chosen for research because the vulnerability of this neighborhood has already been investigated in a collaboration with the University of Padua in 2013-2015 [19].

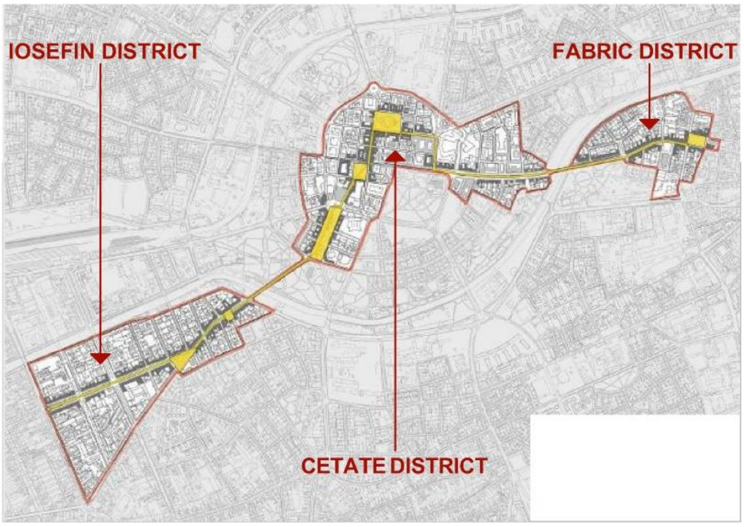
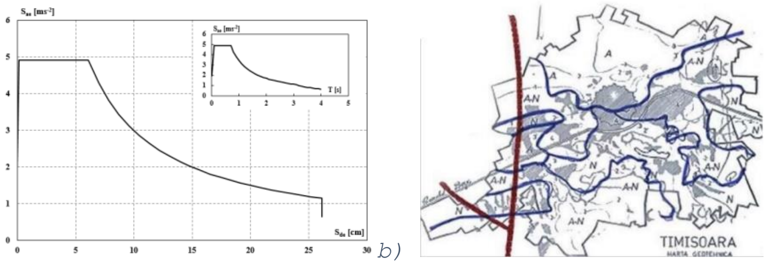


Figure 3. Proposed cultural promenade for Timisoara city [18]

a) b)
Figure 4. The investigated buildings in: a) Iosefin district; b) Fabric area

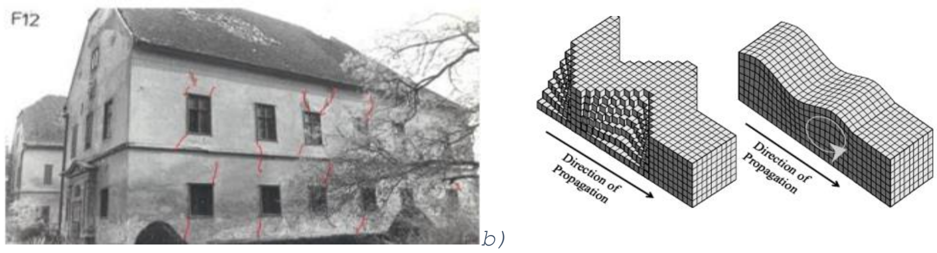
The construction typology is based on the formation of aggregates with closed contours in relation to the streets and inner courtyards [20]. Most of the buildings in the group investigated in Iosefin have a basement, ground floor and one floor, while in Fabric has a basement, ground floor and two floors. Almost all the buildings are located in the street alignment, forming continuous fronts and presenting commercial spaces on the ground floor, respectively residential spaces or offices on the upper floors [17]. Unfortunately, only 10-15% of the investigated buildings have been restored in recent years, the vast majority showing a serious state of decay, which leads to an increase in the level of vulnerability [21]. Regarding the socio-economic analysis, 504 apartments with approximately 1200 inhabitants in Iosefin and 196 companies with 550 employees were identified. In Fabric, the number of registered apartments was 385 with 1000 inhabitants, and the number of companies with 70 with about 250 employees [22]. These data are useful and necessary for assessing possible losses in the event of an earthquake.

Within Romania, there are two important seismic areas, Vrancea and Banat. If in the Vrancea area the earthquakes present magnitudes up to 7 degrees, in the Banat area they are shallow, with magnitudes up to 5.6 degrees, but with strong vertical forces [23]. For Timisoara, the gravitational acceleration according to the design code P100 is 0.20g [24], outlining the seismic spectrum for the Banat area (Fig. 5) [25]. At the local level, in the western part of the city there are two active seismic faults, whose radius of influence is 5-10 km from the investigated historical areas, representing a real risk factor [18].



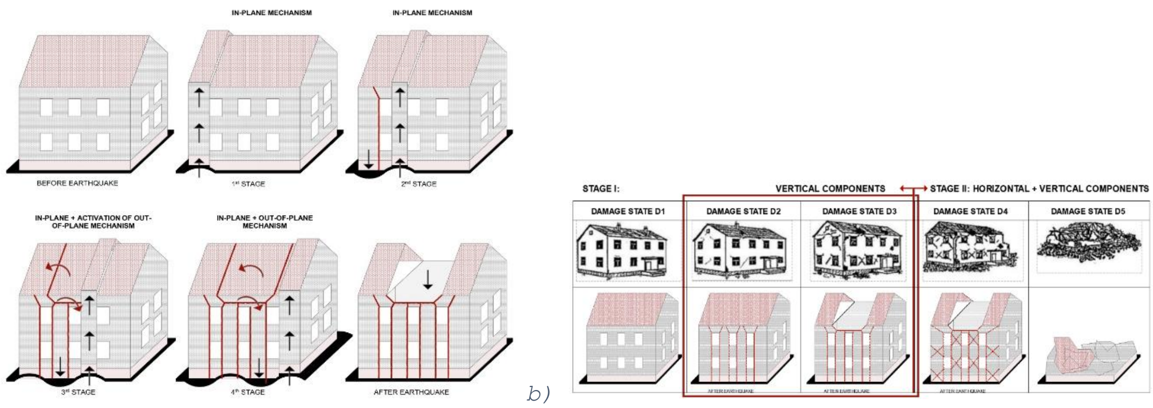
a) b)
Figure 5. Banat seismic spectrum [25] and the seismic faults nearby Timisoara [18]

The strongest earthquake recorded in the Banat area was the one in Banloc, in 1991, about 40 km from Timisoara (measured in a straight line). The damages registered after the earthquake were mainly due to the shear forces and the vertical ones, observing damages at the level of arches, lintels, attics, chimneys [26]. Given the fact that there was a shallow earthquake (11 km focal depth), the vertical forces were comparable to the horizontal ones, as in the case of the earthquakes in L'aquila [27], Amatrice [28] or Christchurch [29], leading to a combination of diagonal and vertical cracks, as seen in Fig. 6 [21]. The main reason for the appearance of vertical cracks is given by the surface waves L and R specific to the areas near the epicenters, which are dangerous for historic buildings and not only (Fig.6) [30].



a) b)
Figure 6. Typical cracks after Banloc earthquake [21] and L and R seismic waves resposable for the vertical craks [30]

In addition to the phenomena of in-plane failure described above, there were also out-of-plane failure mechanisms, especially at the top of the facades. In some cases, areas of complex and rigid trusses collapsed inside buildings, affecting floors and interior walls. Based on the data observed after the Banloc earthquake, the failure mechanism specific to the masonry buildings in the Banat seismic area was defined, observing the strong impact of the vertical forces and the overturning phenomenon at the upper part of the facade (Fig. 7) [21]. Comparing the registered damages with the European macroseismic damage scale, it can be observed that the damage level was of the D2-D3 level, signifying serious damages to non-structural elements and moderate damages to the structural ones (Fig. 7).



a) b)
Figure 7. Specific failure mechanism in Banat seismic area [21] and comparison with the damage distribution scale

In order to be able to make a seismic scenario for Timisoara, the most probable macroseismic intensity was evaluated, by means of two methods. The first is a simplified method that depends on gravitational acceleration, indicating a possible macroseismic intensity 9 [31]. The second is dependent on focal depth, epicenter distance and magnitude, offering more possibilities depending on the location of the epicenter [32]. Considering the two active seismic faults at 5-10 km from the investigated areas, two possible seismic scenarios for Timisoara are outlined, both indicating the same macroseismic intensity with the value 9.

For the 105 buildings that are the subject of empirical analysis, investigation sheets were made (found in the appendices of the doctoral thesis) and aspects such as construction system, regularity in plan and elevation, symmetry, level of conservation of the building were studied, the existence of architectural-artistic values, the position within the urban ensemble, etc. For the 25 buildings considered representative and investigated in detail, complete surveys and a small experimental test were performed. All buildings are made of brick masonry and lime mortar, have massive exterior walls with thicknesses of 40 to 80 cm in the basement and non-structural transverse walls with thicknesses of 10-15 cm. The medial walls parallel with the street front are usually structural. In general, the transverse walls are not connected to the facade, leading to a high risk of out-of-plane failure mechanism activation. At the level of the basement and sometimes of the ground floor there are brick masonry vaults with thicknesses of 15-20 cm, while at the rest of the levels there are wooden floors [18]. The wooden frame is usually complex and rigid, made under German influence, with heights that can accommodate another level. The taller the building, the more important the frame [33].

Depending on the number of levels, the buildings were classified into 3 main categories: typological class type I represented by basement + ground floor buildings, type II basement buildings, ground floor and one floor and typological class type III represented by buildings with 2 or more upper floors. In Iosefin the most common is type II, while in Fabric the most common is type III, among the investigated buildings [18].

With the goodwill of the owners, it was allowed to extract some bricks from inside the investigated buildings, these coming from the basement or attic area. An experimental test was performed on them with the hydraulic press and the sclerometer, in order to determine their compressive strength [34]. By comparing the results obtained with the Romanian Design Code and with other results of similar buildings provided by Prof. Ianca, Prof. Stoian, Prof. Marin from the Polytechnic University of Timisoara, the mechanical properties of the brick masonry were agreed for mechanical analysis, being considered the most unfavorable option, as seen in Table 1 [34].

Table 1. Mechanical properties of the masonry

Mechanical properties	fk [N/mm^2]	fvk0 [N/mm^2]	E [N/mm^2]	G [N/mm^2]	Density [kg/m^3]
Unreinforced masonry	2.35	0.06	2350	940	1800

From an architectural point of view, the buildings in question were influenced by Ottoman and Habsburg culture, generating a mix of styles such as art nouveau, secession and baroque. In the past, buildings used to reflect the status of the owner, marking their importance by height, decoration, respectively the shape and complexity of the roof [35]. In type I buildings, the decoration is simple, usually represented by a few bosses at the corner of the building and profiled cornices. Already in type II there is a different treatment of registers, respectively frames and decorated cornices. Within type III, the facades are complex, presenting even bas-reliefs, sculptures, moldings, and the decorated frontons represent an almost obligatory element.

Next, an empirical analysis of the 105 buildings was performed, based on a simplified method that was proposed by Benedetti and Petrini [3] and later developed by Mazzolani and Formisano [36]. The latter added the last 5 parameters, which also take into account the influence of adjacent buildings. The procedure is simplified, it is based on the allocation of a vulnerability class for each element investigated. Each class (from A to D, A being the most advantageous and D the most vulnerable) has an associated score, and each element has an associated influencing factor. At the end, the weighted average of all the elements is made and the vulnerability index of the investigated building results. The factors considered refer to the quality of the structural materials, the regularity in plan and elevation, the type of foundation and soil type, the complexity of the structure, the type of floors, the level of conservation, as well as other details that may influence the vulnerability. In addition, the last 5 parameters refer to the differences in height from the neighboring buildings, the position within the aggregate (ie corner, end), the presence of staggered floors, structural homogeneity compared to adjacent buildings and differences in the percentage of openings (Eq. 1) [36].

$$I_V = \sum_{i=1}^{n} s_i \times w_i \quad (1)$$

Based on the normalized vulnerability index (Eq. 2) [21], the damage index (Eq. 3) [37] can be determined, which depends on the macroseismic intensity and a distributive factor that influences the vulnerability slope, considered in the literature as 2.3 for predominantly residential buildings. The damage index indicates the probable level of damage, this being between D1 and D5 in order of severity, the first class representing minor damage, the last class representing the possibility of collapse (Table 2) [38].

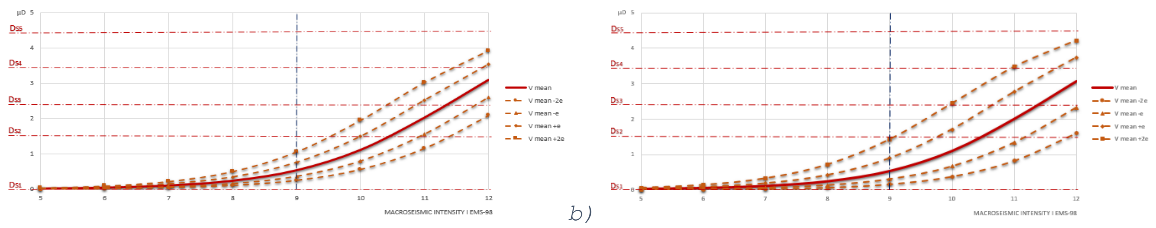
$$V = \frac{I_V - I_{V\,MIN}}{I_{V\,MAX} - I_{V\,MIN}} \quad (2)$$

$$\mu_D = 2.5\left[1 + \tanh\left(\frac{I + 6.25 \times V - 13.1}{\Phi}\right)\right] \quad (3)$$

Table 2. Correlation between damage index and most probable damage state [38]

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)

This methodology, in unaltered form, was applied on the 105 buildings in Iosefin and Fabric, considering the macroseismic intensity 9. Two investigations were performed, both for buildings considered as isolated structures (ie analyzing only the first 10 parameters) , as well as for structures considered in the aggregate, analyzing all 15 parameters. The vulnerability curves drawn for the first 10 parameters for each building indicated a probable level of damage D1, as well as the average level of damage. For all 15 parameters the situation remains unchanged, keeping the average level of damage D1 (Fig. 8). Making the vulnerability maps, it can be seen that a single building presents a risk of slight damage (Fig. 9).



a) b)

Figure 8. Average vulnerability curves for the 105 investigated buildings: a) for the first 10 parameters; b) for all 15 parameters

Figure 9. Empirical vulnerability maps for: a) Iosefin; b) Fabric district

Analyzing these results, it could be concluded that a macroseismic intensity 9 is not dangerous for Timisoara, an aspect in contradiction with the description of this intensity itself, which predicts that it causes significant damage and is felt intensely. Also, the damages registered at Banloc contradict the previous results, making it necessary to investigate in detail and calibrate the empirical methodology. In this sense, the need to draw some capacity curves is outlined, which should describe the performance point of the building and allow the comparison of the capacity of the structure with the earthquake demand.

The mechanical analysis was performed with the Tremuri program [39], on 25 buildings considered to be representative. Tremuri discretize the structure into macro elements (lintels and piers) connected by rigid nodes. Following the non-linear pushover analysis, it was observed that approximately 40% of the macro-elements suffer damage from shear, bending or tension. Although there is no possibility of loss of load-bearing capacity, a general level of damage D2-D3 can be estimated, in some isolated cases even D4 (Fig. 10).

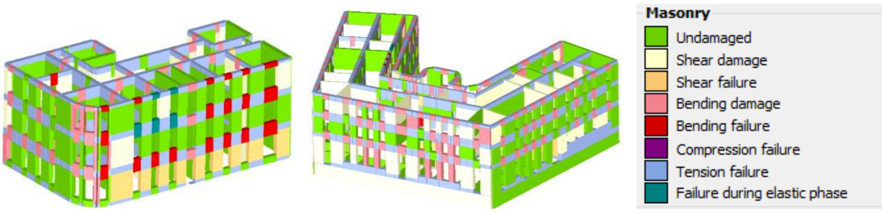


Figure 10. Rezultatele analizei neliniare asupra unora dintre cladiri

Carrying out the nonlinear analysis, the base shear forces were investigated, respectively the top horizontal displacement for the service limit state and the ultimate limit state. Based on these values, the mechanical vulnerability index could be determined, as the ratio between the capacity and demand (Eq. 4) [40].

$$V_{MEC} = \frac{\Delta_y}{\Delta_u} \tag{4}$$

Applying the formula, it was observed that the average mechanical vulnerability index is relatively similar for the 3 types of buildings, being between 0.32 and 0.34 (the maximum possible value being 1). Applying the same methodology for determining the probable level of damage described above, mechanical vulnerability curves were drawn, indicating in this case a minimum level of damage D1-D2, contrary to what can be seen by directly studying the results of nonlinear analysis. In order to check the correctness of the damage levels, another method was applied, that of the relative displacement between the levels (Eq. 5). Based on the value of the interstorey drift, the probable level of damage can be assessed (Table 3) [41].

$$I_D = \frac{\Delta_{u,n} - \Delta_{u,n-1}}{h} x100 \qquad (5)$$

Table 3. Interstorey drift damage state assessment [41]

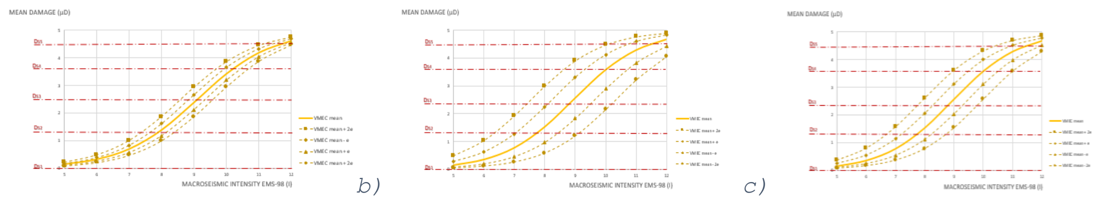
URM	Damage state D2	Damage state D3	Damage state D4	Damage state D5
	ID < 0.1%	0.1%<ID<0.3%	0.3%<ID<0.6%	0.6%<ID

Applying this method, it was observed that type I of buildings has a probable average level of damage D2, type II D3, while type III has an average probable level of damage D3-D4. These damage states are consistent with the nonlinear analysis, the scale of macroseismic intensity, respectively the damages observed after the Banloc earthquake and claim that the method of assessing the probable level of damage is not adapted for surface earthquakes. Thus, the formula for estimating the level of damage requires adaptation.

The purpose of the adaptation is to increase the probable level of damage by at least one level, so that for the macroseismic intensity 9, it indicates D2-D3 for the investigated buildings. For this, only one parameter from the basic formula has been modified, the one that influences the distribution of the curve, a parameter that in the literature is usually modified according to the local conditions and the particularities of the area. Based on multiple studies, it was concluded that the parameter should be changed from 6.25 to 12.5 (Eq. 6).

$$\mu_D = 2.5\left[1 + \tanh\left(\frac{I + 12.50 \times V - 13.1}{\Phi}\right)\right] \qquad (6)$$

Considering this new parameter, the mechanical vulnerability curves were restored, indicating this time an average damage state D2 for type I of buildings, respectively D3 for the other two types (Fig. 11). These new results being in accordance with the previous observations, we proceeded to apply the adapted methodology on the entire set of 105 investigated buildings.



a) b) c)

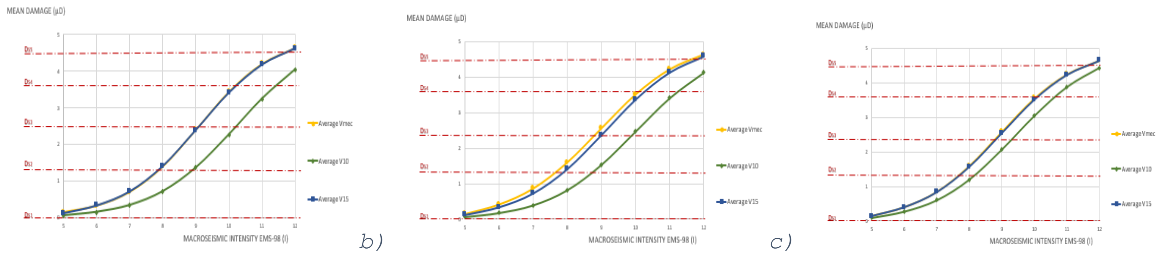
Figure 11. Average mechanical vulnerability curves: a) for typological class type I; b) for type II; c) for typological class type III

In the first stage, the empirical vulnerability curves for buildings considered as isolated structures were restored, indicating the average damage state D2 for all 3 types of buildings. In the second stage, the empirical vulnerability curves for buildings considered in the aggregate were restored, the average level of vulnerability increasing up to D3 for typological class type III. Regarding the distribution of damage, it can be seen that the level of damage is higher in the Fabric area, but no building has a risk of collapse (Fig. 12).

a) b)

Figure 12. Seismic vulnerability maps following the proposed procedure: a) Iosefin area; b) Fabric district

For a detailed analysis of the results, the empirical vulnerability curves were compared with the mechanical ones and it was observed that there is a good correlation especially between the mechanical and empirical vulnerability curves for all 15 parameters (Fig. 13). The new results are also in accordance with the interstorey drift method, respectively with the damages observed following the Banloc earthquake. However, the empirical method that considers only the first 10 parameters tends to underestimate the level of damage sometimes even with a class, indicating the need to consider the influence of neighboring buildings.



a) b) c)

Figure 13. Comparison between average empirical and mechanical vulnerabiliby curves after adaptation for: a) typological class type I; b) type II; c) type III

Chapter four represents the correlation of the field of civil engineering with that of architecture. After adapting the methodology for the Banat seismic area, it was wanted to adapt it so that the cultural component is taken into account. In this sense, it was decided to consider four important pillars in assessing vulnerability, these being structural integrity, architectural value, urban or symbolic value, as well as socio-economic value. As architectural-artistic values, we can consider all the elements discussed in the previous chapter, such as original carpentry and plaster, statuettes, bas-reliefs, moldings, paintings, floors, etc. As urban values, we can consider the relationship with the urban or natural environment, the importance of location within the city, belonging to a homogeneous site, symbolism, importance for shaping the urban silhouette or street profile, and other features [42]. For the socio-economic component, we can consider the association of the building with certain historical moments or significant personalities, its importance in the community memory, the possible relationship with the intangible heritage, respectively the type of functions and the economic value of the building. Finally, following the recommendations of the Romanian methodological code for the classification of historical monuments [43], literature and personal observations, we came to consider a total of 42 parameters, divided into the 4 main categories (Table 4).

Table 4. Seismic vulnerability assessment influenced by the cultural value form

%	Criteria	No.	Element	Class				Weight
				A	B	C	D	
70%	STRUCTURAL	1	Vertical structure organisation	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
		11	Different height between current and adjacent buildings	-20	0	15	45	1.00
		12	Location of the building into the aggregate	-45	-25	-15	0	1.50
		13	Staggered floors	0	15	25	45	0.50
		14	Structural or typological heterogeneity	-15	-10	0	45	1.20
		15	Opening area percentage difference	-20	0	25	45	1.00
						$I_{V\ STRUCT}$		
15%	ARCHITECTURAL ARTISTIC	16	Representative architectural style for the area	0	10	15	25	1.50
		17	Age, importance of the build époque	0	10	15	25	1.20
		18	Original woodwork/joinery	0	10	15	25	1.00
		19	Original stucco, brick, floors or ceilings	0	10	15	25	1.00
		20	Original statues or bass-reliefs	0	10	15	25	1.00
		21	Original gable/fronton	0	10	15	25	1.00
		22	Original balconies and railings	0	10	15	25	1.00
		23	Original mosaics or stone work	0	10	15	25	1.00
		24	Original paintings or frescoes	0	10	15	25	1.00
		25	Conservation state of artistic assets	-5	10	15	25	1.00
		26	Authenticity/ originality (global, elements)	0	10	15	25	1.00
		27	Official monument (national, regional, local, protected area) status	0	10	15	25	1.50
		28	Particular construction techniques/materials	0	10	15	25	0.50
		29	Conservation state of original materials	-5	10	15	25	0.50
		30	Representative historical events	0	10	15	25	0.50
		31	Archaeological site	0	10	15	25	1.50
		32	Representative/ original wooden framework	0	10	15	25	1.00
		33	Past restoration work	-5	10	15	25	1.00
						$I_{V\ ARCH\text{-}ART}$		
10%	URBANISTIC	34	Importance in contouring the street profile	-5	10	15	25	1.50
		35	Importance in contouring the urban silhouette	-5	10	15	25	1.50
		36	Annexes, relation with the urban pattern	0	10	15	25	1.00
		37	Location (central area, touristic area)	0	10	15	25	1.50
		38	Representative/particular shape of the roof	0	10	15	25	1.00
						$I_{V\ URB}$		
5 %	SOCIAL ECONOMIC	39	Public/social functions	0	10	15	25	1.50
		40	Importance for the local community memory	-5	10	15	25	1.00
		41	Economic value	0	10	15	25	1.50
		42	Cultural functions	0	10	15	25	1.50
						$I_{V\ SOC\text{-}EC}$		
						$I_{V\ CULT}$		

The vulnerability index is determined based on the same principle of the empirical methodology, by the weighted average sum (Eq. 7). The structural category remains the most important, as the load-bearing capacity of the building is considered to be a priority in the process of vulnerability assessment.

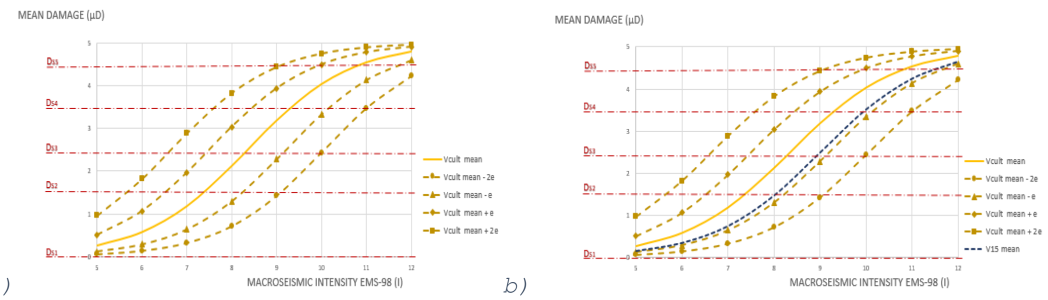
$$I_{V\ CULT} = 0.70 \times \sum_{i=1}^{15} s_i \times w_i + 0.15 \times \sum_{i=16}^{33} s_i \times w_i + 0.10 \times \sum_{i=34}^{38} s_i \times w_i + 0.05 \times \sum_{i=39}^{42} s_i \times w_i \quad (7)$$

However, after obtaining this vulnerability index, it is necessary to mitigate the importance of the studied site. For this purpose, an attenuation factor is determined as an arithmetic mean that takes into account the age of the investigated site, population, tourist importance, worldwide recognition, as well as the general state of conservation (Table 5).

Table 5. Attenuation factor form

Parameter		Options	Points (p_i)
1	Age of the urban area	Ancient period (before year 500)	0.30
		Classical period (500 – 1500)	0.25
		Modern period (1500 - 1945)	0.22
		Contemporary period (1945- present)	0.20
2	Population	Very high populated (> 1 million inhabitants)	0.30
		High populated (< 1 million inhabitants)	0.25
		Moderate populated (< 300000 inhabitants)	0.22
		Low populated (< 100000 inhabitants)	0.20
3	Tourism	Very touristic city	0.25
		Touristic city	0.23
		Little touristic city	0.22
		Not a touristic city	0.20
4	Worldly recognition	UNESCO site	0.35
		Continental importance	0.30
		National importance	0.25
		Regional importance	0.20
5	Conservation state	Poor	0.30
		Moderate	0.25
		Good	0.23
		Very good	0.20
		A_F	

The vulnerability index obtained is normalized in the range 0-1, so as to allow a 1 to 1 comparison with empirical and mechanical methods. The same formula for evaluating the level of damage adapted for the Banat seismic zone is applied to this normalized index. Thus, for all types of buildings the level of most probable damage increases with the consideration of cultural value, but less for type I and considerably for type III. The increase is directly proportional to the level of decoration in buildings, and their importance at the urban and social level. The new average damage states are D3-D4, as seen in Figure 14a. Making a comparison between the empirical vulnerability curves and the cultural curves, it is observed that for typological class type I the increase in vulnerability is only 6%, while for type III, it is 16% (Fig. 14b).

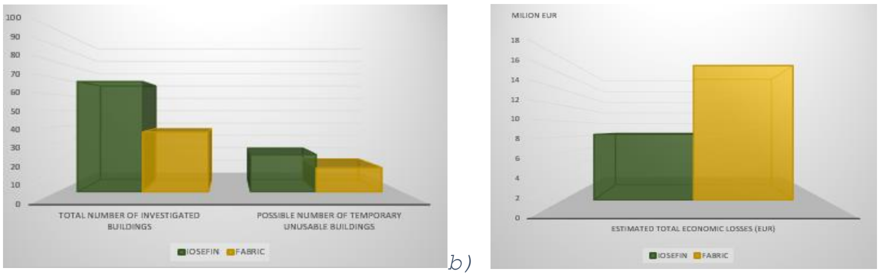


a) b)

Figure 14. Average seismic vulnerability curve influenced by the cultural value or all 105 buildings and its comparison with the original empirical average curve

If the damage states have been defined and adapted to both the Banat seismic area and the cultural component, the next step is to create loss scenarios. Their role is to be able to perform a cost-benefit analysis between what the prevention measures would mean in relation to the recovery ones. Thus, the aim was to identify possible losses in terms of buildings or physical damage, human lives, cultural losses, respectively economic losses. For this purpose, loss assessment formulas from the literature were used and supplemented with new formulas proposed for further evaluations [22]. For economic losses, the construction costs per square meter associated with each country or area are considered, respectively the gross domestic product and the costs of one night hotel accommodation for the investigated site [44]. All these formulas are detailed in the thesis.

However, the results are very important, because they reveal an interesting situation. Regarding the number of buildings that will need repair works, the number of people that will need relocation for a period of time, and the number of people who may lose their jobs or income, within the Iosefin neighborhood they are higher. However, in terms of financial losses, they are higher in the Fabric neighborhood. Why does this phenomenon happen? Because even if there are fewer buildings in Fabric, they are much more degraded and implicitly more vulnerable, so they will have a higher level of damage. This means extensive repair works, longer relocation periods for residents, respectively longer periods of inactivity for companies (Fig. 15). Consequently, this aspect should be considered by the local authorities, and Fabric should have priority for rehabilitation works, in order to reduce the possible costs of reconstruction and recovery.

a) 

b)

Figure 15. Losses assessment for the considered seismic scenario: a)buildings that will need rehabilitation works; b) financial losses

Additionally, the thesis proposes a method for assessing artistic architectural losses, because the average damage state is above D2, which means extensive damage to non-structural elements. It is considered that there can be three cases: structural architectural-artistic elements, such as important arches and vaults, valuable trusses, masonry walls made with a certain ancient technique, etc. Or tehere can be non-structural artistic elements, but connected with the structure, such as a valuable painting on a structural wall, an important floor or a valuable coffered ceiling. The third case refers to individual artistic elements, such as a railing or a sculpture. The results (Fig. 16) show that in the case of buildings in Timisoara, there is a risk of 35 to 60% of irrecoverable loss of valuable arch-artistic components.

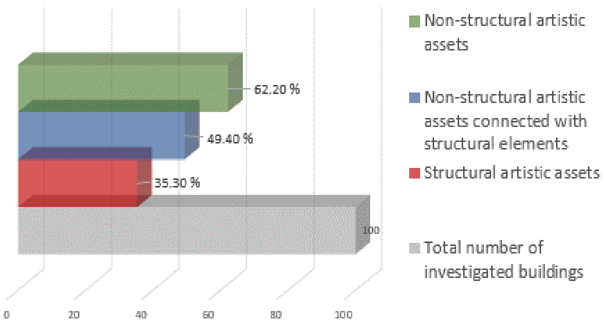
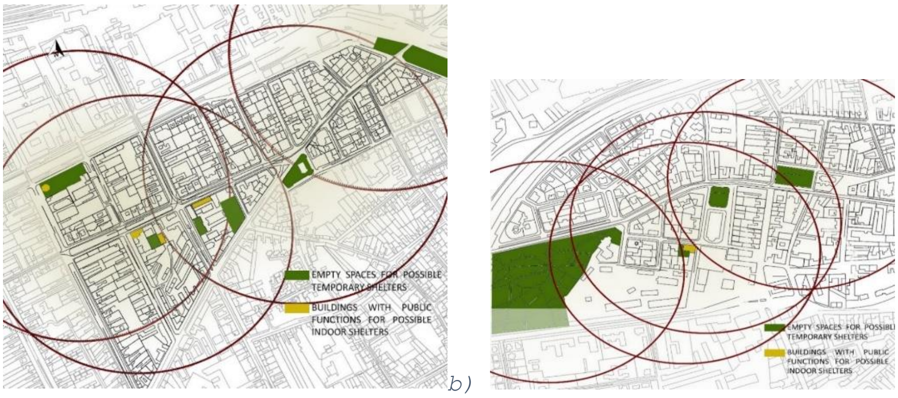


Figure 16. Architectural-artistic assets loss assessment

The main advantage of the extended methodology is to allow the prioritization of rehabilitation works considering not only the structural component, but also the cultural one. In the case of buildings with the same probable level of damage, the affected area or the number of affected persons can be considered as an additional criterion. Thus, it is ensured the preservation of a large number of heritage buildings for future generations and a small number of people affected in case of earthquake.

Extrapolating the results of the proposed methodology, the foundations can be laid for a plan to reduce the seismic risk for the city of Timisoara, which should contain two major stages: pre and post event. In the prevention stage it is recommended to organize multidisciplinary commissions for vulnerability assessment. Based on these reports, priority lists, evacuation plans, technical expertise and consolidation projects can be made for the buildings considered to be the most vulnerable, as well as a relocation plan. In the post-earthquake stage, it is recommended to evacuate and relocate those affected, consolidate and rehabilitate the buildings, as well as economic and social policies to return to normalcy [45].

As a last stage of the analysis at macro level, the possible evacuation spaces for the two areas were mapped (Fig. 17), these being represented by free construction spaces where refugee camps can be placed, respectively by public buildings that can be closed shelters. Although at first glance for both neighborhoods there is at least one place of evacuation less than 500 meters from any building, it must be considered that the most vulnerable buildings turned out to be the corner ones, which could lead to a blockade of evacuation routes. To this end, detailed future studies are recommended to define safe routes in the Iosefin and Fabric neighborhoods.



a) b)

Figure 17. POssible evacuation spaces for: a)Iosefin; b)Fabric district

Chapter five uses the results of the nonlinear analysis, in order to identify common failure mechanisms within the 25 masonry buildings. The first part of the chapter resumes the evaluation of the interstorey drift, but not to determine the probable damage state, but to see at what values it can be considered that the first cracks appear, respectively that the load-bearing capacity limit is reached. It is thus observed that the service limit state is reached at values of up to 0.06% of the displacement, respectively the last limit state at values of up to 0.32%. As the height of the building increases by one level, it allows a final lateral movement up to 8% higher.

In order to determine the in-plane failure mechanism for the investigated buildings, it was studied where and how the first cracks appear within each type of buildings. Thus, 4 types of failure were determined (Fig. 18):

- Appearance of cracks due to bending forces at the top of the facades
- The appearance of cracks due to bending and shear forces, also at the upper part of the facades
- Appearance of cracks due to bending forces at both the upper and middle part for tall buildings
- Respectively the appearance of cracks due to bending and shear forces at the upper and middle part, also for tall buildings

In principle, the bending cracks appear mainly at the lintels, while the diagonal shear cracks appear in the pillars. For the first type of buildings, the first type of failure mechanism is the common one. For the second type of buildings, the failure mechanism types 2 and 3 are common, with small exceptions, while for the typological class type III, the failure mechanisms 3 and 4 are common.

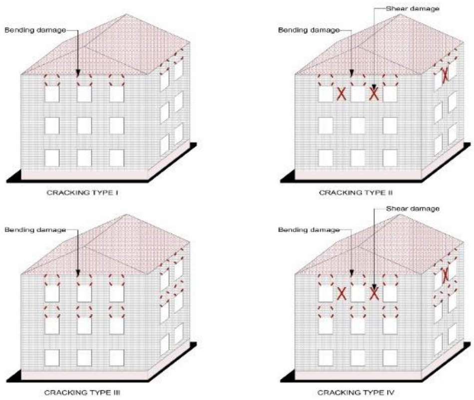


Figure 18. Specific failure mechanism types for : a)Iosefin; b)Fabric district

When analyzing the base shear forces, it was observed that they increase from one typological class of building to another by about 50%, mainly due to the increase in mass. Regarding the top horizontal displacements allowed by the structures, it can be observed that they increase from one type of buildings to another, especially at type III. The very high increase between typological classes type II and type III is due to the fact that among the investigated buildings, those of type III are much larger, having the length of the main facade about 3 times longer than type II. At the same time, the height of the building increases by up to 50%.

Regarding the ductility of the investigated structures (Eq. 8) [46], on average, the ductility factor of the studied buildings has a value of 2.5, being small differences between the types of buildings (Fig. 19a).

$$\mu_\Delta = \frac{\Delta_u - \Delta_y}{\Delta_y} \tag{8}$$

In order to better understand the response of the building, the behavior factor (Eq. 9) was determined for each of the typological classes in relation to the ductility previously determined [47]. Thus, it was observed that the average value of the behavior factor is 1.8-2, with larger differences on the transverse direction y (Fig. 19b).

$$q = (2\mu_\Delta - 1)^{1/2} \tag{9}$$

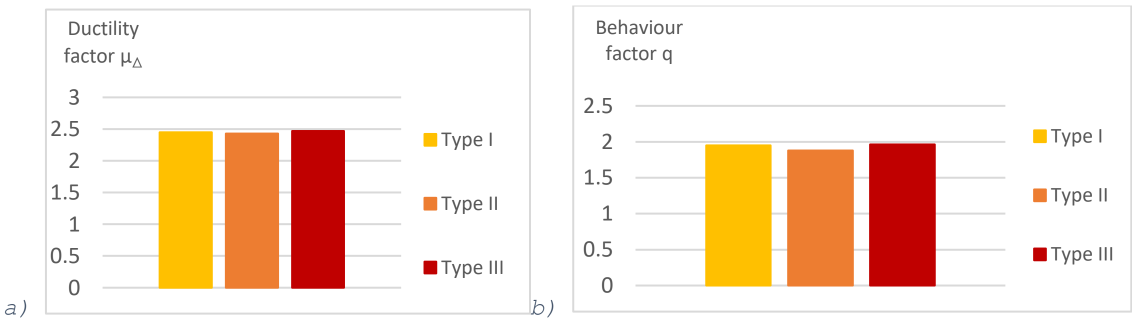


Figure 19. Average ductility and behavior factor for the investigated buildings

At the beginning of the thesis, the hypothesis was formulated according to which all the investigated masonry buildings are short-period structures. To verify the statement, the capacity curves of the investigated buildings overlapped with the seismic spectrum determined for the Banat area (Fig. 20). It can be observed that, for all three typological classes, the own vibration period is shorter than the control period of the response spectrum, so the basic hypothesis is confirmed.

a) b) c)

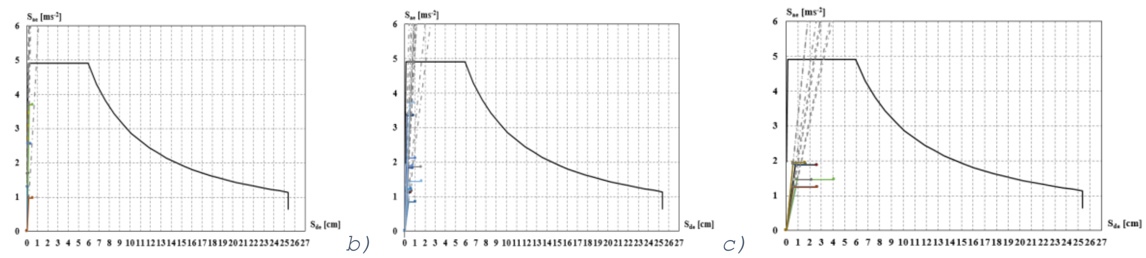


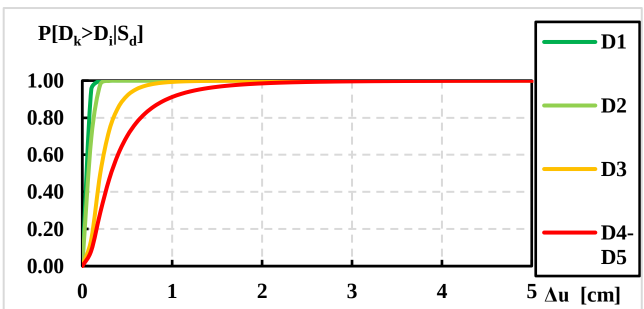
Figure 20. Investigation of the type of structure for: a) typological class type I; b) type II; c) typological class type III

A last stage in the process of extrapolating the information obtained through nonlinear analysis is the drawing of the fragility curves for the typological classes in Timisoara. The role of these curves is to indicate, statistically, at which final displacements a certain level of damage is likely to occur. The method of determination is a mathematical one, considering that a certain level of damage occurs when a certain percentage of the yielding or maximum displacement is reached (Eq. 10). Based on this information, a distributive matrix is actually generated, which has a standard deviation influenced by the ductility of the structure (Eq. 11) [48].

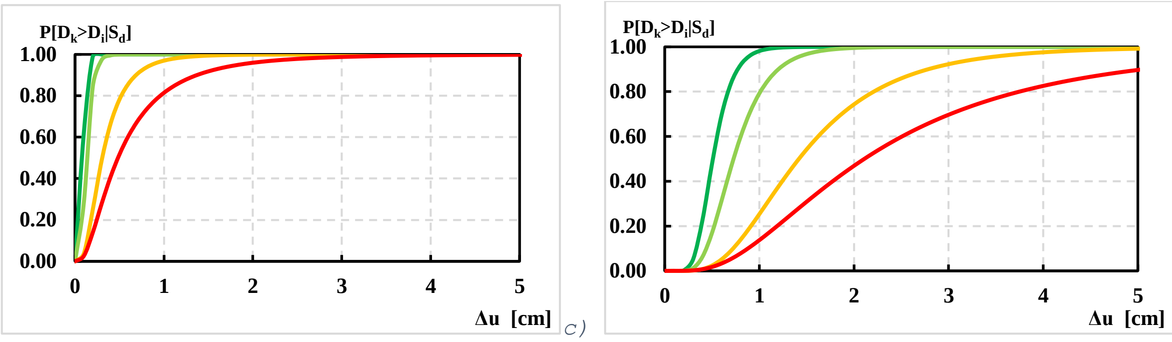
$$S_{D1} = 0.7\ x\ \Delta_y \tag{10}$$
$$S_{D2} = 1.5\ x\ \Delta_y$$
$$S_{D3} = 0.5\ x\ (\Delta_y + \Delta_u)$$
$$S_{D4} = \Delta_u$$
$$P[D_k|S_{de}] = \Phi[\frac{1}{\beta}\ x\ \left(ln \frac{S_{de}}{S_{de,DS}}\right)] \tag{11}$$

Applying the methodology, the fragility curves for the first typology of buildings were determined (Fig. 21a). Knowing already from the previous subchapters that the average lateral displacement for typological class type I is 0.30 cm, there can see that there are 100% chances to reach the damage state D2, about 70% for damage state D3, respectively below 45% for the damage states D4-D5. The situation is similar for type II (Fig. 21b), where the average lateral displacement is 0.5 cm, slightly increasing only the chances of reaching the damage state D3. For the third type of buildings (Fig. 21c), where the average lateral displacement is 2 cm, there is 100% chance of obtaining the damage state D2, approximately 75% chances for D3 and less than 50% chances for D4-D5. These observations indicate that for all three typological classes, the chances for D4-D5 damage states are below 50%, so there is more likely to have only moderate damage to the structural elements and it is very likely to have extensive damage to the non-structural ones.

a)



b)

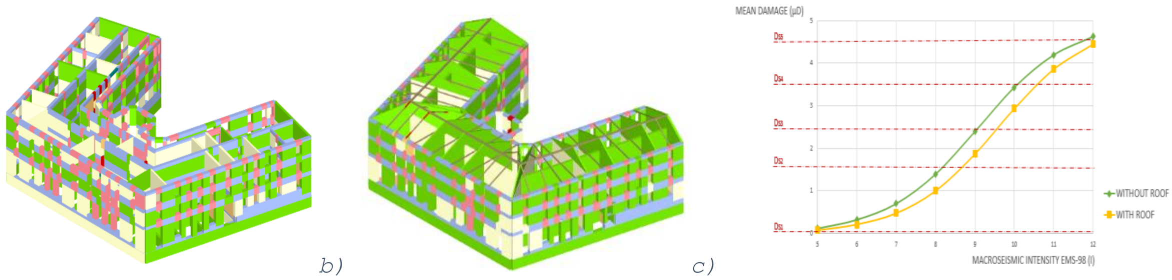


c)

Figure 21. Average fragility curves for: a) typological class type I; b) type II II; c) typological class type III

As preliminary recommendations for improving the load-bearing capacity of the investigated structures, two hypotheses have been made that open future research directions.

The first refers to the consideration in the calculation of the rigid wooden framework. Based on the simulations performed with Tremuri, with and without the considered truss, it was observed that it can limit the maximum lateral displacement of the external walls, leading to a reduction of the mechanical vulnerability index by 10 to 15 percent. Also, it is worth investigating the observation according to which the compression of the facade walls by the complex framework leads to a redistribution of the appearance of cracks from the entire facade to the corners of the buildings [49].



a) b) c)

Figure 22. Comparison of damage distribution and vulnerability curves without and with roof considered [49]

The second hypothesis refers to the application of simple consolidation solutions with fiber-based materials, considering for simulation four options [50]:

- Without any consolidation
- Reinforcement with polymeric fibers type ARV100, applied at a step of 100 cm
- Top with ARV100 fibers, but at a smaller step, of only 50 cm
- Respectively with galvanized steel fibers type Geosteel G600, applied at a 100 cm step

All materials used are from the company Kerakoll [50] and can be easily applied on the outside of buildings. Additional simulations are recommended to be made in the future to see how they can be applied so as to avoid areas with cornices or decorative consoles. It can be observed that there is a reduction of seismic vulnerability by 10-15% for reinforcements with ARV100 fibers, respectively by up to 30% for reinforcements with Geosteel G600, changing the probable level of damage with one class (Fig. 2. 3).

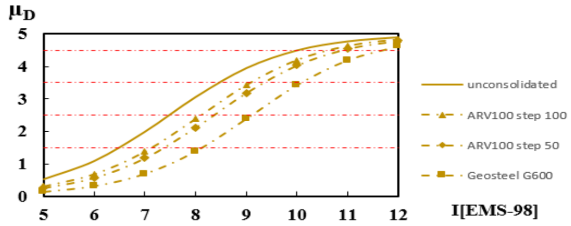


Figure 23. Comparison of vulnerability curves before and after consolidation

Chapter six represents the conclusion of the entire thesis. The entire work is based on the research that the late Professor Victor Gioncu began over 30 years ago in this field. The need to propose a rapid methodology for assessing seismic and cultural vulnerability is underlined by the large number of buildings with heritage value in Timisoara, but also by the limited financial possibility of the owners to use detailed technical expertise. Thus, the issue of heritage protection is the responsibility of local authorities, which could easily use the proposed methodology for all historic buildings in the city, quickly and easily obtaining a list of priorities for rehabilitation works.

On a large scale, the thesis proposals are in accordance with the concerns of ICOMOS, aiming to reduce the seismic risk and protect the heritage, but also the local communities. The large volume of data collected and processed is the result of a multidisciplinary collaboration with colleagues and students, as well as with other researchers from abroad. Even if no experimental tests were possible due to time, space and financial limitations, the thesis results were calibrated based on the real response of the buildings following past earthquakes, these representing the tremendous natural laboratory of the Banat seismic area.

Regarding the personal contributions within the thesis, it is noted:

- Proposing a first simplified methodology for assessing seismic vulnerability for near-field areas
- The harmonious combination for the first time of the structural criteria and of the architectural-artistic, urbanistic, social-cultural and economic ones
- Creating a first database and the first curves and vulnerability maps for the city's historic districts
- Evaluation of the most probable failure mechanisms for each typology of historical buildings present in the city
- Investigating the impact of rigid and complex wooden framework, respectively of fiber-based reinforcement materials on the load-bearing capacity of brick masonry structures
- Preparation of a first losses scenario in case of earthquake for Timisoara and promotion of first ideas for defining a plan to reduce urban risk

Thus, the personal contributions illustrated in the thesis represent an innovative, efficient approach in the process of assessing and reducing the seismic vulnerability of historical urban centers, to be continued for future improvements and developments.

The thesis opens multiple future research directions, in fields such as:

- seismic vulnerability of masonry aggregates
- out-of-plan failure mechanisms for historic masonry buildings
- fragility curves for several types of buildings and aggregates
- detailed investigation of the impact of the wooden framwork and simple consolidation methods
- various seismic scenarios for differn epicentral distances and different focal depths

The research results were published periodically in several papers, two of which are in the international journal Engineering Failure Analysis with impact factor 2.897, another 12 papers were published in volumes of ISI-indexed international scientific events, 2 papers in indexed journals Scopus, 2 papers in volumes of some international conferences indexed Scopus, respectively other 3 papers in volumes of other scientific manifestations. In total, 21 scientific papers have been published, which so far have been cited in 42 scientific articles, of which 13 in articles in journals with impact factor and 6 in volumes of ISI indexed events. During the ICEFA 2018 conference, organized by Elsevier publishing house and Engineering Failure Analysis journal, the presented work received the award for the best poster. As a dissemination of information, the research results were presented in 9 conferences, of which 6 abroad and 3 in the country.

In conclusion, the PhD thesis presents valuable contributions in the field of seismic vulnerability of historic masonry buildings, while opening future research directions of great interest. Through a multidisciplinary approach, the research in question is an innovative approach, of high quality and of real interest for reducing seismic risk in the Banat area.

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