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Seismic Vulnerability Assessment and Loss Estimation of an Urban District of Timisoara

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Abstract. The seismic risk evaluation of built-up areas is associated to the level of earthquake hazard, building vulnerability and level of exposure. It is well known that the large-scale vulnerability assessment is a very important topic for the protection of historical buildings and the mitigation of effects of natural phenomena on the built-up. In 2020 Timisoara will be the Capital of European Culture and, therefore, the knowledge of the number of unusable and collapsed buildings under possible earthquakes is a crucial point to plan suitable future intervention strategies from structural and urban points of view. Based on these premises, the proposed research is conducted in collaboration with the University of Naples "Federico II" with the main purpose to focus on the seismic vulnerability evaluation of buildings located within an urban-sector of Timisoara through the EMS-98 macro-seismic approach. First of all, the typological vulnerability classes of buildings according to the RISK-UE method have been defined in order to classify them from typological and structural viewpoints. Subsequently, a vulnerability form appropriately conceived for masonry aggregates has been filled for the study area buildings and the typological fragility functions have been derived for them aiming at identifying the most vulnerable constructions. Finally, parametric analysis has been carried out by varying the seismic magnitude and site-source distance in order to estimate the seismic loss estimation under earthquakes.

1. Romanian seismicity

Romania is a country with almost 20 million citizens, located in the Eastern Europe, with a very complex landscape, including the Danube River, the Carpathian Mountain and the Black Sea shore. The country is characterized by two major seismic zones, very different between each other [1]. The first and most important is Vrancea seismic zone, which affects the SE part of the country and is located on the Moesian Platform, over three tectonic units in contact [2]. This type of crustal block generates intermediate-depth earthquakes (60-200 km) with stress regime predominantly compressive at depth and magnitude over 7 (Richter scale) [3]. The second seismic zone in Romania is Banat area [4], located in the western part of Romania, between the Pannonia Depression and the Carpathian Mountains and it is characterized by small depth events, high activity, with magnitude that does not exceed 5.6 on Richter scale, presenting very strong vertical forces with expected PGA equal to 0.2g considering a return period of 475 years [5].

Timisoara is the 3rd biggest city in Romania, with more than 300000 inhabitants, developed along Bega River, first mentioned as a place in year 1212. During the Ottoman administration since 1552, Timisoara developed a very strong defence system, based on massive masonry walls that protected the city. Starting with year 1716, with the Habsburgic administration, the city developed outside the defence walls, creating the residential zones Iosefin and Fabric. Recently, Timisoara has been selected to be European Capital of Culture for 2020, so the study focuses attention on the assessment of large-scale seismic vulnerability of an urban sector within the historical centre represents in fact, an important aspect for mitigation risk and for the protection of people and buildings.

2. Large-scale seismic vulnerability assessment

The seismic vulnerability of the sub-urban sector of the old city centre of Timisoara was evaluated. Aiming at implementing a speedy seismic evaluation procedure for masonry aggregates; it has been used the new vulnerability form based on Italian methodology proposed by [6], [7], which has been used in recent years for the seismic vulnerability assessment of several aggregate stock in many cities, Figure 1.

Parameter	Class score (s)				Weight (w)
	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. In-plane regularity	0	5	25	45	0.5
6. Vertical regularity	0	5	25	45	0.5÷1
7. Type of floor	0	5	15	45	0.75÷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 building in the aggregate	-45	-25	-15	0	1.5
13. Number of staggered floors	0	15	25	45	0.5
14. Structural or typological heterogeneity among adjacent structural units	-15	-10	0	45	1.2
15. Percentage difference of opening areas among adjacent facades	-20	0	25	45	1

Figure 1. The vulnerability form for the assessment of building compounds

This new form is based on the Benedetti & Petrini vulnerability index method [8], subsequently updated with five other parameters that take into account the effects of mutual interaction between structural units (S.U.) in aggregate conditions during a seismic event [9].

Furthermore, more detailed criteria are used to assign scores to the considered parameters were more developed. The vulnerability index (I_v) can be calculated using the Eq. (1).

$$I_V = \sum_{i=1}^{15} S_i \times W_i \qquad (1)$$

where, S_i are the scores associated with the vulnerability classes (from A, better, to D, worst) and W_i are the weights associated with each parameter. Moreover, the average multiplier of the vulnerability index has been calibrated based on the proposed works [10], [11] as a ratio of the average of the typological vulnerability indices. This calibration was made necessary in order to increase the vulnerability indexes calculated with the previously described form because the Italian methodology defines a lower damage threshold than the actual state of damage observed after the on-site inspection. Subsequently, expected damage will reflect the class of buildings present in the considered urban sector.

The study sub-urban sector is located in Uniri Square. The square is characterized by a Baroque architectural style of the early 1900's with an extension of 15000 m^2. The structures are characterized by homogeneous typological classes. They are unreinforced masonry structures (URM) composed by

solid brick walls. The number of floors varies from 2 to 3 (Figure 2) and the average surface area is 400 m^2. From a structural point of view, most of the buildings examined have vaults on the ground floor and on the first and second levels wooden or steel floors and few of them also RC floors [12].
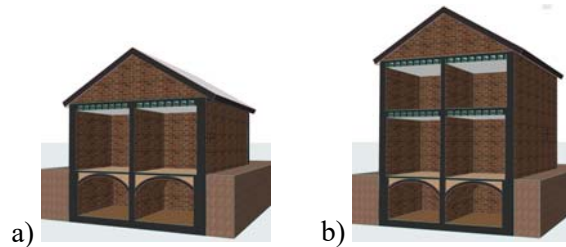

Figure 2. Structural typologies identification: a) two floors; b) three floors

According to the Building Typology Matrix (BMT) [13], it was possible to classify buildings from a typological and structural point of view. This sector is composed by 21 buildings: M3.1 class masonry structures with wooden floor (11%), M3.4 masonry structures with RC floors (2%) and 8% of the buildings surveyed in this area are in reinforced concrete, but they are not taken into consideration in the study conducted. (Figure 3).
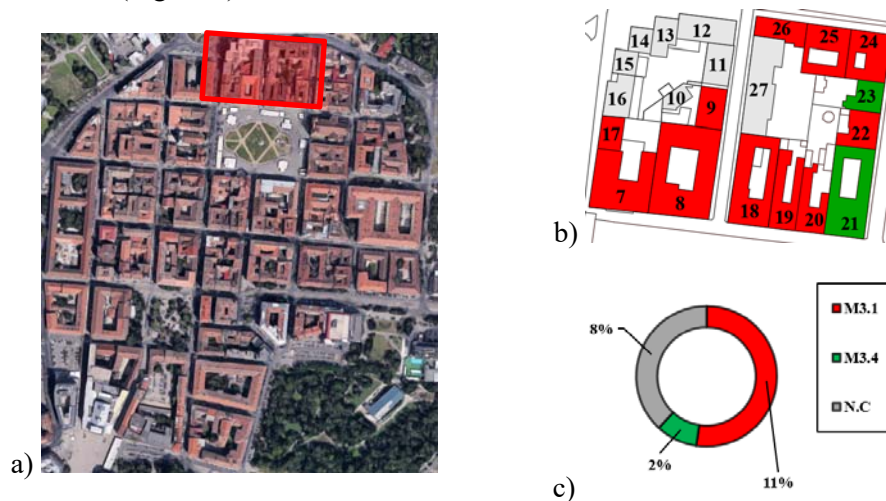
Figure 3. Study area: a) bird-eyes view; b) sub-urban sector; c) typological characterization

Based on these premises, the vulnerability of the sub-urban sector has been computed according to the vulnerability form, the results are shown in Figure 4.
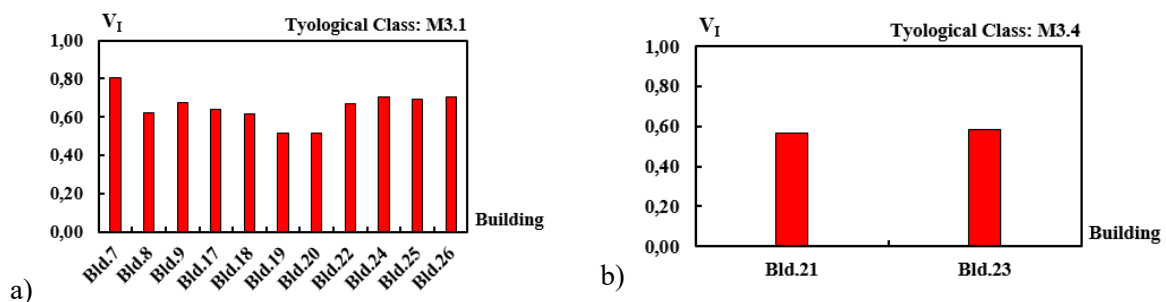
Figure 4. Ranking of buildings belonging to M3.1 (a), M3.4 (b) typological classes

From the analysis of the results, it is possible to notice that the most vulnerable building of the typological class M3.1 is the number 7, which has V_I= 0.81. On the other hand, for the typological class

M3.4 the vulnerability indices are respectively 0.56 and 0.58 for buildings 22 and 23. However, it can be seen that buildings belonging to class M3.4 (reinforced concrete floors) are less vulnerable than buildings M3.1 (wooden floors) because globally they guarantee a box behaviour of the structure, with less deformations induced by the earthquake. Furthermore, even if the building no.7 presents good structural condition, it has a high vulnerability index compared to other buildings.

This condition is due to its position in aggregate (head) constrained only on two sides and is not a favourable condition in case of seismic event. Similarly, buildings 21 and 23 occupy an intermediate position; presenting reduced vulnerability indices compared to other structural units in the aggregate condition. Therefore, the vulnerability curves shown in Figure 5 have been plotted to estimate the collapse probability of analysed structural units when they are subjected to seismic actions.

They are used to estimate the expected degree of damage of building classes for given seismic intensity and they are function of normalized vulnerability index (V_I), expressed by Eq. 2, used in the macroseismic methodology [14]. The hazard expressed in terms of macroseismic intensity (I) and finally of the ductility factor (Q) assumed equal to 2.3 [15], which describes the ductility of the class of buildings analysed applying Eq. 3.

$$V_i = \left[\frac{I_V - (\sum_{i=1}^{15} S_{min} \times W_i)}{\sum_{i=1}^{15} S_{max} \times W_i} \right] \tag{2}$$

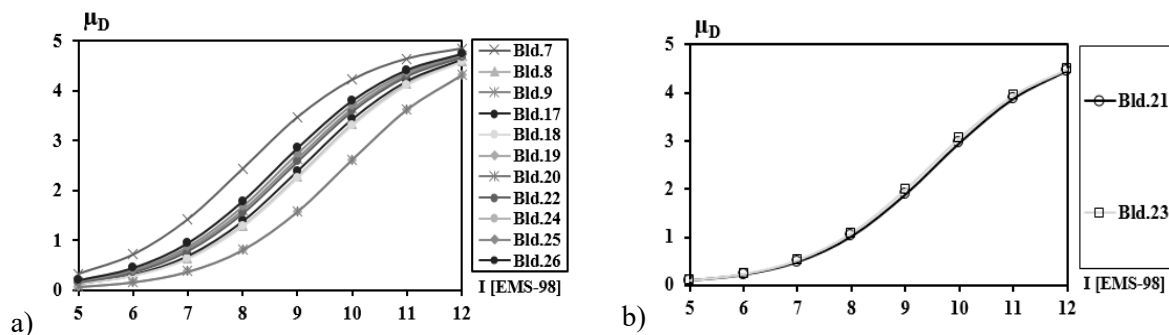$$\mu_D = 2.5 \left[1 + \tanh\left(\frac{I + 6.25 V_I - 13.1}{Q} \right) \right] \tag{3}$$

Figure 5. Vulnerability curves for main typological classes: M3.1 (a), M3.4 (b)

Table 1 shows the damage thresholds considered [16] for the assessment of damage scenario.

Table 1. Correlation between mean damage grade intervals and damage state

Mean damage range [μ_D]	Damage state [D_i]	Damage level [DL]
0-1.5	D1	Slight
1.5-2.5	D2	Moderate
2.5-3.5	D3	Substantial to heavy
3.5-4.5	D4	Very heavy
4.5-5	D5	Collapse

Considering the representative damage parameter μ_D, which is defined in the EMS-98 scale, the expected number of buildings that undergo a certain damage level has been determined (Figure 6).
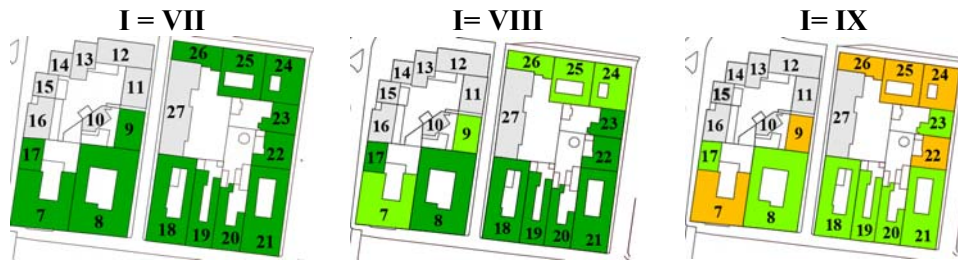
Figure 6. Seismic damage scenario for the sub-urban sector varying intensity level

From the results, it can be noticed that for increasing seismic intensity, the expected damage tends to increase. In fact, for seismic intensity I= VII, all buildings reach damage threshold D1. Contrary, for a seismic intensity equal to IX, will be 53% (D2) and 46% (D3) respectively.

3. Predictive parametric damage scenario analysis

The analysis of the damage scenario using a parametric approach allows analysing in detail the degree of damage associated with a generic structural system when it is subjected to a natural event. With reference to the case study examined, the damage associated with a seismic event is considered by varying the input magnitude. From the historical analysis (Figure 7) of the earthquakes occurred in the Banat region, the maximum magnitudes occurred in the range [4-6] were selected.
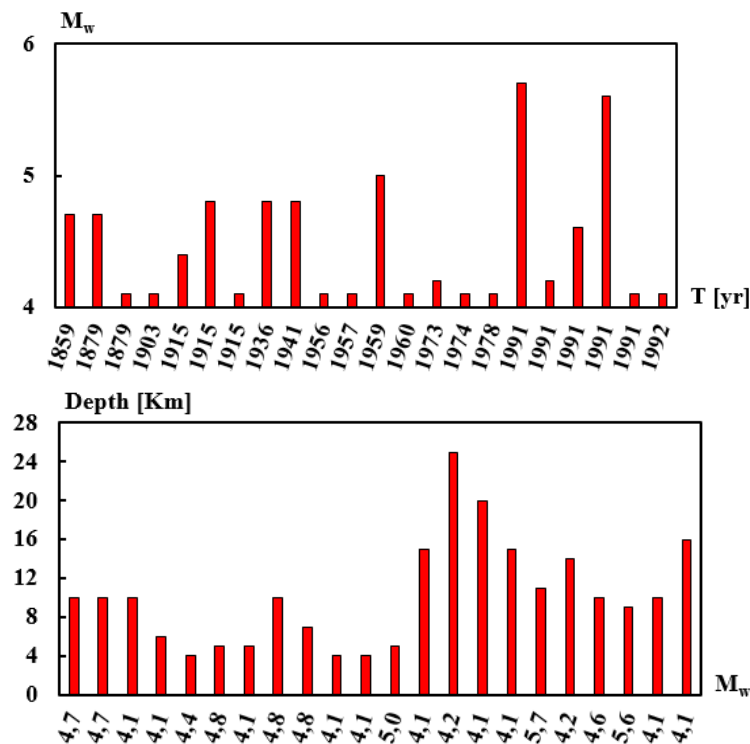
Figure 7. Maximum magnitude occurred in the Banat Region

The severity of the damage was analysed thanks to the predictive analysis in which, during the earthquake, buildings with the same structural characteristics would be subjected to a damage that decreases when the site-source distance (R) is increased.

The site-source distance depends respectively on the epicentre distance (d) and the focal depth (h_f). In the specific case, for the previously defined distances were varied in the range $5 \leq h_f \leq 25$ km.

Subsequently, the attenuation law defines the macroseismic intensity according to EMS-98 from the formulas (4), (5) proposed by [17].

$$I = 1.45 \cdot M_W - 2.46\ln(R) + 8.166 \tag{4}$$

$$R = \sqrt{d^2 + h_f{}^2} \quad [\text{km}] \tag{5}$$

$$I = 1.5 \cdot M_W - 3.5\log(D) + 3 \tag{6}$$

Furthermore, the equation (6) proposed by [18] is considered in order to have a wider evaluation of the seismic intensity useful for a more accurate future calibration of the proposed method. This formulation, according to the MSK scale, has been calibrated on the basis of the earthquakes occurred in Timisoara and is only a function of the site-source distance (D). In the present work, reference is made to the previously described formulations as they take into account epicentre distance (d) and focal depth (h_f). The results are shown in Table 2.

Table 2. Magnitude-macroseismic intensity correlation law

M_W	d [Km]	h_f [Km]	I [EMS-98]	I [MSK]
	5	5	9	7
	10	10	7	6
4	15	15	6	5
	20	20	6	5
	25	25	5	4
	5	5	11	8
	10	10	9	7
5	15	15	8	7
	20	20	7	6
	25	25	7	6
	5	5	12	10
	10	10	10	9
6	15	15	9	8
	20	20	9	8
	25	25	8	7

Based on the above, it was possible to define a seismic scenario as a function of the focal depth (h_f) for seismic events occurring that characterized the distribution of seismic damage. Considering the representative damage parameter μ_D, which is defined in the EMS-98 scale, the expected number of buildings that undergo a certain damage level has been determined (Figure 8).
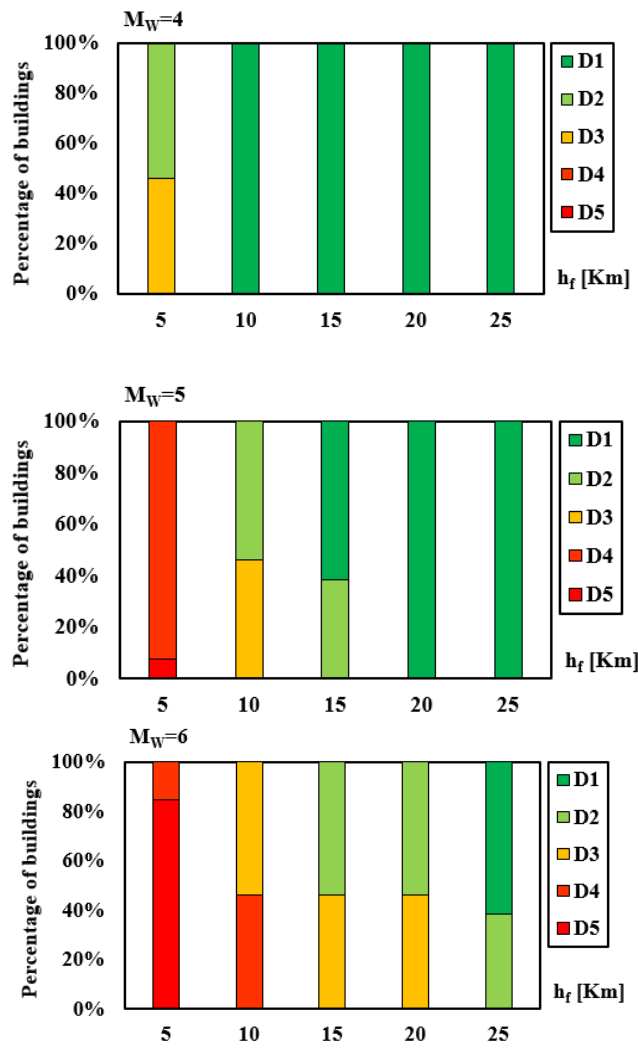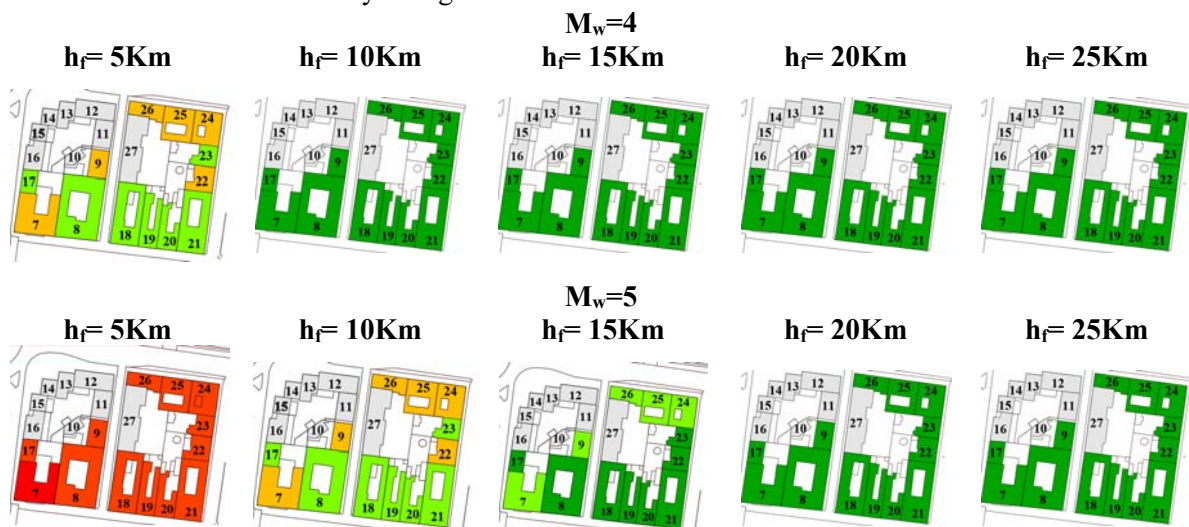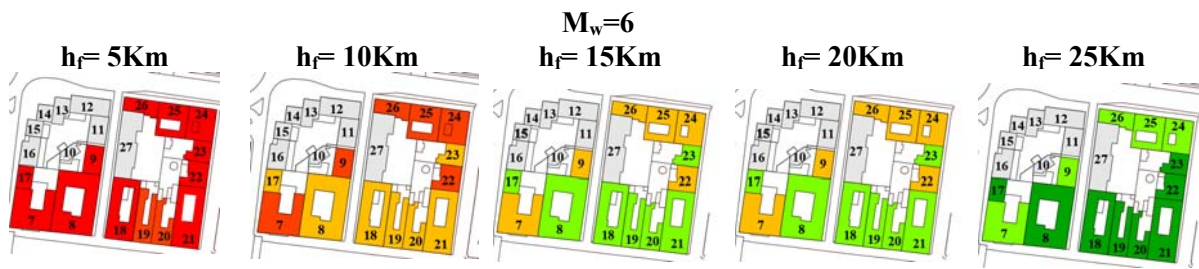
Figure 8. Parametric seismic damage scenario for the sub-urban sector varying focal depth

The results are shown briefly in Figure 9.

Figure 9. Seismic damage scenario varying magnitude and focal depth

A first result shows that for low intensity (Mw = 4) the expected damage for the subsector is between D2 (53%) and D3 (46%) for h_f = 5 km, instead when the focal depth increases, the expected damage tends to decrease progressively.

In particular, for M_w= 5 the worst scenario is for h_f =5 Km. In fact, 92% of the buildings of the sub-sector analysed will suffer D4 damage (very heavy) while the remaining 0.07% will suffer D5 damage (collapse). For h_f = 10 Km, there is a reduction of the expected damage, in fact, 53% of the buildings will suffer damage D2, while 46% give D3. For focal distances greater than 15 km, the expected damage is equal to D1 because the localization of the hypocentre attenuates the propagation of the seismic wave and therefore the expected effects are reduced.

Finally, for Mw = 6, 84% of buildings suffer D5 damage (collapse) and the remaining 15% suffer D4 damage. Moreover, for h_f = 10 Km, 53% of buildings will suffer damage D3 and 46% D4 damage.

4. Prediction of collapsed and unusable buildings loss estimation

The estimation of functional loss seen as unusable and collapsed buildings plays an important role in urban planning and retrofit strategies because it provides beneficial measures for structural repair and safety of life.

The model adopted is based on degrees of damage concerning the probability of exceed a certain level of damage. According to [19] and the following values applied in this study, unusable and collapsed buildings follow these Equations:

$$P_{unusable} = P[D3] \times W_{ei,3} + P[D4] \times W_{ei,4} \tag{7}$$

$$P_{collapse} = P[D5] \tag{8}$$

where P[D_i] is the probability of the occurrence of a certain damage grade (from D1 to D5) and $W_{ei,j}$ are multiplier factor that indicate the percentage of buildings that suffer or are considered unusable. Although the SSN [20] and Hazus [21] methodologies have indicated distinct values for this multiplier factor, the following values applied in this study: $W_{ei,3}$=0.4 and $W_{ei,4}$=0.6 and shown in Figure 10.

In this context, the results show how the effects induced by the earthquake of different magnitude and for different focal depths, produce unusable and collapsed buildings. In fact, with reference to the estimate of unusable buildings, it can be noted that for the most unfavourable condition, it is for Mw = 5 with 55% (M3.1) and 66% (M3.4) of buildings that could declare themselves unusable.

On the other hand, the estimate of collapsed buildings shows that the most difficult scenario is for Mw = 6 with focal depth hf = 5 km. In this case, the buildings that could collapse are respectively 81% (M3.1) and 100 % (M3.4).
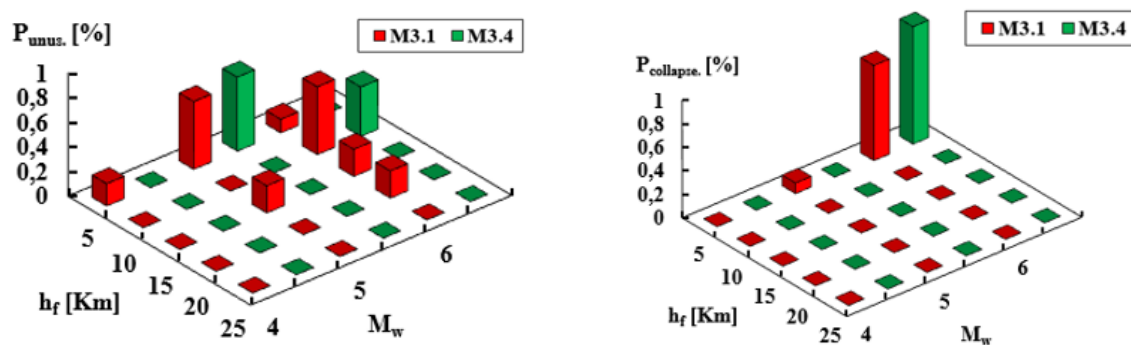
Figure 10. Unusable and collapsed buildings varying focal depth

5. Conclusion

The illustrated study made it possible to evaluate the seismic vulnerability and the post-earthquake damage scenario of a sub-urban sector in the centre of Timisoara.

Timisoara in 2020 will be the Capital of European culture and the prediction of large-scale damage scenarios; will allow safeguarding the historical heritage and life of people.

Initially, the study area was characterized by a typological and structural point of view and a stock of 21 buildings divided into classes M3.1, M3.4 respectively. The analysis of the vulnerability on a municipal scale was performed using the vulnerability form for historical aggregates. This analysis allowed us to identify the most vulnerable buildings belonging to the previously defined typological classes. The results obtained show that the most vulnerable buildings are those belonging to the M3.1 class. In addition, it was possible to analyse the degree of damage by the typological vulnerability curves, which show the nonlinear correlation between the macroseismic intensity, assessed by the EMS-98 scale, and the expected damage. From the results obtained, it emerges that for modest seismic intensities $V \leq I \leq VI$ buildings exhibit no damage ($0 < \mu D < 1$), while for high intensity the analysed buildings undergo extensive damage or collapse ($3 < \mu D < 5$).

Subsequently, on the basis of the historical earthquakes occurred, the parametric analysis was carried out in order to identify, by varying the focal depth, the worst case scenario by means of seismic attenuation laws. From the results, it is noted that the most severe seismic scenario occurs for a magnitude $M_w = 6$ with a focal depth of 5 km. In fact, 84% of buildings suffer D5 damage.

The Italian methodology should be calibrated in the future considering the local characteristics of Banat earthquakes and the observed damages on buildings after registered earthquakes in Timisoara.

Finally, the study of damage scenarios is very important especially in a global vision of the problem as it allows identifying the number of buildings that could be unusable and therefore mitigate the seismic risk and plan the structural interventions in a timely manner.

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