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Seismic vulnerability of old confined masonry buildings in Osijek, Croatia

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Abstract. This paper deals with 111 buildings built between 1962 and 1987, from various parts of the city of Osijek, for which, through the collection of documentation, a database is created. The aim of this paper is to provide the first steps in assessing seismic risk in Osijek applying method based on vulnerability index. This index uses collected information of parameters of the building: the structural system, the construction year, plan, the height, i.e., the number of stories, the type of foundation, the structural and non-structural elements, the type and the quality of main construction material, the position in the block and built-up area. According to this method defining five damage states, the action is expressed in terms of the macroseismic intensity and the seismic quality of the buildings by means of a vulnerability index. The value of the vulnerability index can be changed depending on the structural systems, quality of construction, etc., by introducing behavior and regional modifiers based on expert judgments. Since there is no available data of damaged buildings under earthquake loading in our country, we will propose behavior modifiers based on values suggested by earlier works and on judgment based on available project documentation of the considered buildings. Depending on the proposed modifiers, the seismic vulnerability of existing buildings in the city of Osijek will be assessed. The resulting vulnerability of the considered residential buildings provides necessary insight for emergency planning and for identification of critical objects vulnerable to seismic loading.

Keywords: seismic vulnerability assessment; building typology; macroseismic method

1. Introduction

Although Croatia is located in an earthquake prone area (it is at risk from earthquakes producing ground accelerations ranging up to 0.38 g), only metropolitan areas with significant seismic risk are in need of analysis. More than half of Croatia's territory (56.22%), with more than one third (1,633,529) of the total population, is classified as a high risk seismic zone.

The majority of buildings built in the last decade are in accordance with Eurocode 8 provisions for earthquake-resistant design concepts. Nonetheless, a significant number of old stone and masonry buildings are not in accordance with any of these requirements. The assessment of

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seismic risk and seismic vulnerability of existing building stock is fundamental for the establishment of priorities in a long-term prevention policy.

The standard definition of risk is the probability of damage and consequent loss to a given element at risk, over a specified time. Loss is defined as the human and financial consequences of damage, including injuries or deaths, the costs of repair, or loss of revenue. The difference between risk and loss is often negligible. Consequently, based on their definition, these terms may be used interchangeably sometimes.

Since the standard definition of risk is a probability or likelihood of loss, between zero and one, it may be more appropriate to express risk as

$$Risk = Hazard \times Vulnerability, \quad (1)$$

while loss depends on the value of the exposure at risk, given by

$$Loss = Hazard \times Vulnerability \times Exposure. \quad (2)$$

The first step in protecting the city from an earthquake disaster is to form and possess a theoretical prediction of the consequences: structural damage as well as socio-economic losses that may happen after the occurrence of the earthquake. In fact, it is crucial to assess the effects of any potential earthquake in order to prepare for management during catastrophic situation. As well as anticipating and taking appropriate measures to reduce the vulnerability and expected losses on the part of guaranteeing urban resilience.

The selection of a given seismic vulnerability assessment method depends on the nature and objective of the study, available information, characteristics of the buildings or the group of buildings under study, suitable method of assessment (qualitative or quantitative) and organization of data collection and decision makers (Preciado *et al.* 2015a). Qualitative methods are used to evaluate the seismic vulnerability of a large group of buildings in a quite general manner and allow obtaining a vulnerability qualification in terms of seismic vulnerability that could range from low to high. On the other hand, quantitative methods are used to evaluate one building in a detailed way and evaluate the vulnerability in numerical terms (e.g., ultimate force, displacement capacity and failure modes) (Preciado *et al.* 2015b). Isik and Kutanis (2015) carried out performance based assessment of 16 reinforced concrete (RC) buildings in Bitlis. Structural performance was determined by employing the non-linear methods described in the latest Turkish Earthquake Code published in 2007. Their results showed that 53% of those buildings were determined as having Fully Operational performance level, with 13% of them in the Life Safety performance level. Ranjbaran and Hosseini (2014) evaluated analytically the vulnerability of confined masonry buildings. They provided nonlinear dynamic analysis of two-story confined masonry buildings with a common plan as a reference structure. In their study, the damage level is calculated based on the probability of exceedance of loss vs a specified ground motion in the form of fragility curves. Apart from these analytical vulnerability methods, empirical methods based on the observation of damage suffered during past seismic events were implemented. Eleftheriadou and Karabinis (2013) conducted an evaluation of damage probability matrices (DPMs) from observed seismic damage data. DPMs were obtained for typical structural types and are compared to existing matrices derived from regions with similar building stock and soil conditions.

To evaluate the vulnerability evaluation for each building, we followed the vulnerability index method (VIM) as the initial vulnerability assessment approach in this study. Vulnerability index is obtained by combination of data from different building typologies in a specific area collected by observation in situ. This method is also called ‘indirect’ because it shows the relationship between seismic action and the response through the vulnerability index. The seismic action has to be defined in terms of macroseismic intensity and the seismic quality of the buildings has to be described by means of a vulnerability index, which value can be changed depending on the structural systems, quality of construction, etc., by introducing behavior and regional modifiers which are based on expert judgments.

There are no available data of damaged buildings under earthquake loading in our country. Therefore, we proposed behavior modifiers based on values suggested by earlier works and on judgment based on available project documentation of the considered buildings in the database. We translated the obtained vulnerability index values into vulnerability classes defined in EMS-98 since most damage reports and vulnerability assessment are more easily compared using EMS-98.

The main objective of this article is to determine the effect of the modifier on the final size of the vulnerability index and to determine the influence of the construction year, the application of seismic norms, number of floors, state of conservation, etc., on the earthquake vulnerability of confined masonry wall. For this reason, when applying the VIM method, only confined masonry buildings in the city of Osijek were chosen.

2. Study area

Osijek is the fourth largest city in Croatia and it is the largest city in Slavonia with a population of 108,048 (according to the 2011 census). The city is located along the banks of the river Drava at an elevation of 90 meters (Fig. 1). The city of Osijek, with an area of 169.94 km^2, is divided into the following 7 zones; Stari grad (Old Town), Tvrđa (Fort), Gornji grad (Upper Town), Donji grad (Lower Town), Novi grad (New Town), Cvjetno naselje (Floral settlement), Industrijska četvrt (Industrial quarter), and Retfala.

Fig. 1 Geographic view of Osijek with selected buildings

2.1 Seismicity of the region

Croatian territory is a part of the Mediterranean zone of the Alpine-Himalayan seismic belt and comprises several distinct geotectonic units: the Pannonian Basin, the Eastern Alps, the Dinarides, the transition zone between the Dinarides and the Adriatic Platform, and the Adriatic Platform itself. The seismicity is mostly expressed in the coastal part (the Dinarides), because of tectonic processes related to the collision of the Adriatic Platform and the Dinarides (e.g., Prelogović *et al.* *1*982, Aljinović *et al.* 1984). The seismogenetic faults there are mostly the reverse ones, and the tectonic movements have predominantly tangential components (Herak *et al.* 1996). While the Pannonian Basin is characterized by rare occurrence of large events which is typical of intraplate seismicity (Markušić *et al.* 1998). In this area, tectonic movements are predominantly vertical on steeply dipping faults (e.g., Aljinović *et al.* 1984, Herak *et al.* 1996). A map of the most important seismogenic faults is presented in Fig. 2.

The seismicity of Croatia is characterized by earthquakes of medium-large magnitude spread all over the country. Relying on the data on spatial relations between geological formations and recent tectonic movements, Skoko and Prelogović (1989) divided the Croatian territory into five seismotectonic provinces - the southern and the western margins of the Pannonian Basin, its central part, the uplifted parts of the Dinarides and the Adriaticum. Markušić and Herak (1999) provided the first consistent seismogenic zoning and they proposed seventeen zones, which may serve as sound basis for seismic hazard studies of the investigated region.

The seismicity of Croatia is represented by the catalog compiled from the Croatian Earthquake Catalog (Herak *et al.* 1996), which is regularly updated each year. Croatian earthquake catalogue contains information (focal depth, magnitude, coordinates of the epicenters, intensity, time, etc.) of

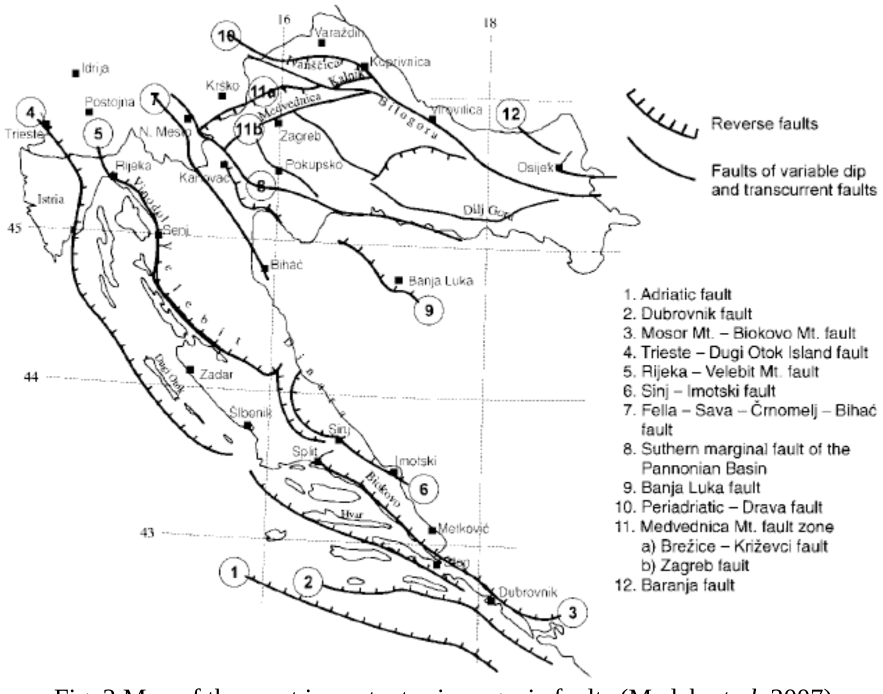


Fig. 2 Map of the most important seismogenic faults (Medak *et al.* 2007)

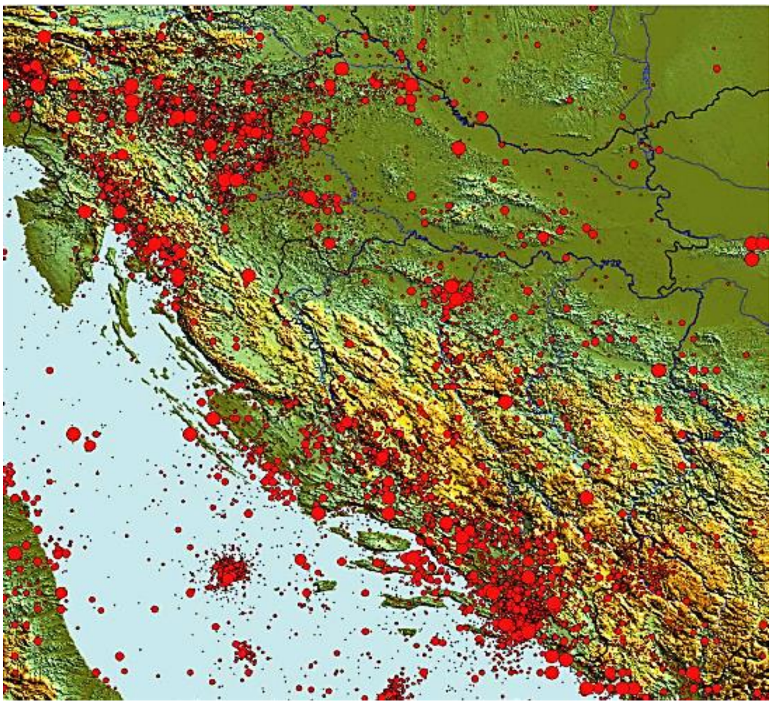


Fig. 3 The epicenters of earthquakes according to Croatian catalog of earthquakes from B.C. - 2011 (more than 55000 earthquakes) (http://www.kartografija.hr/tl_files/Hkd/dogadjaji/HKD_2012_MHerak.pdf)

more than 55,000 earthquakes in Croatia and surrounding areas since the seismic hazard depends on earthquakes whose epicenters are situated several hundred kilometers from the monitored area (Fig. 3).

The seismic hazard can be assessed at both regional and local scales by using two predominant approaches: one being deterministic and the other probabilistic. The deterministic approach is based on the presumption that historical seismicity provides enough information on the expectance of a seismic hazard in the region, while the probabilistic one studies the region's seismicity and seismotectonic characteristics to gather its seismic hazard associated to a certain probability of occurrence (Lantada *et al.* 2010).

Probabilistic Seismic Hazard Assessment (PSHA) determines all possible earthquake scenarios that are expected to hit the area in which research is conducted, including all possible combinations of magnitude, distance and frequency of occurrence of earthquakes of different sizes. This method depends on the availability of a catalogue of earthquakes. It is most often used to obtain seismic hazard curves representing the relationship between ground motion parameters and return period. The parameter used to describe the intensity of ground motion is usually the earthquake intensity (I_{max}, MCS) or the peak ground acceleration (a_{max}, g). The observed period depends on the risk which is taken; for "ordinary" buildings it is typically a period of 50 years and a probability of 10%. Therefore, for a specific location, the risk can be defined by claiming that exceeding the amount a_{max}=0.25 g is expected with a probability of 10% over any 50 years. This event will be repeated on average every 475 years, so it is often talked about the dangers of a return period of 475 years.

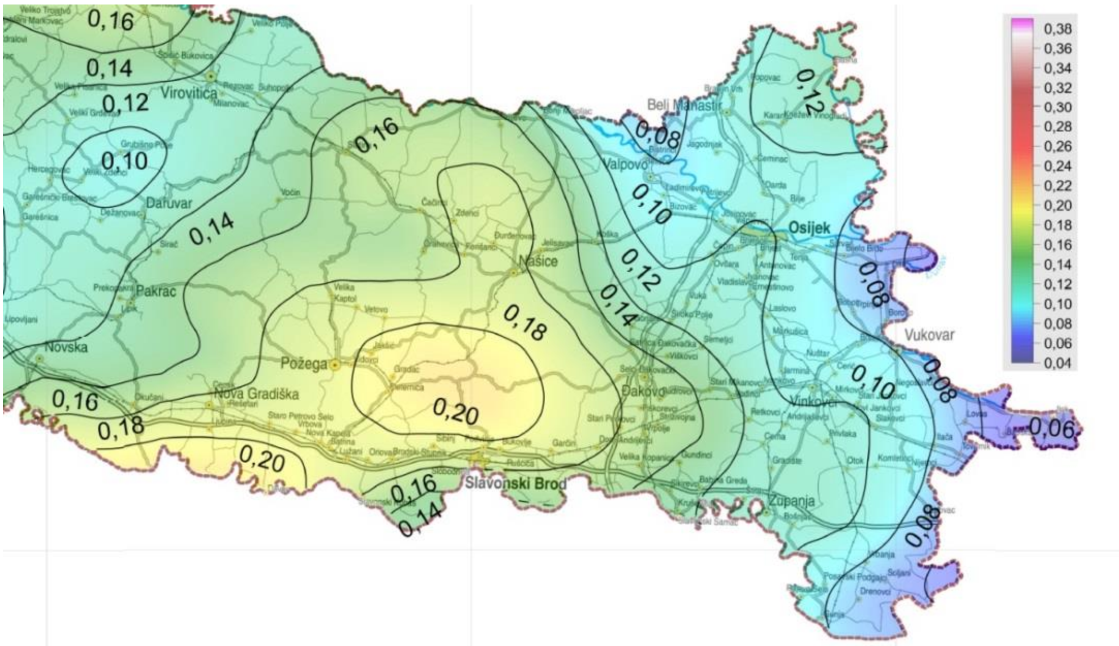


Fig. 4 Part of the Seismic hazard map for Croatia - map of Slavonia and Baranja (Herak 2012) for return period of 475 years

For Croatia, seismic hazard is presented with two maps (Herak 2012), which are accepted as a part of the National Annex to EN 1998-1 (2011). Hazard is expressed in terms of the peak horizontal ground acceleration which is exceeded on average once in 95 or 475 years. Fig. 4 shows the map where the reference peak ground acceleration of type A for the return period of 475 years has a probability of exceedance of 10% in 50 years. According to EN 1998-1 (CEN 2004), soil type A is defined as the ground where the velocity of propagation of seismic waves exceed v>800 m/s and is composed of rock or other rock-like geological formations, including at most 5 meters of weaker material at the surface.

The peak horizontal ground acceleration for the city of Osijek is 0.11 g according to this seismic hazard map for Croatia (Fig. 4).

3. Selected buildings

Building inventory is a database of buildings for each of the typologies within a particular classification system. Preparing an inventory is a very important part of research in the assessment of losses which is time consuming and financially very demanding. In order to obtain a building inventory that is time acceptable and accessible from a financial point of view, data from all available sources have to be gathered. Usually, it is data such as: the purpose of the building, year of construction, height, utilization, value, location of the building, the occupancy rate, etc. Possible sources for the creation of a regional inventory of buildings are: the state database, a database of regional, local and private sector, and data inventory from previous studies of losses and seismic hazards.

The existence of a catalogue of building typology enables one to analyze the vulnerability of each building type, including the influence of the geometric and/or structural modifiers. Unfortunately, a standard building typology catalogue for Croatia has not been generated. Therefore, the first step is to provide data about the buildings and population in a typical urban area in Croatia. This has been started for the city of Osijek.

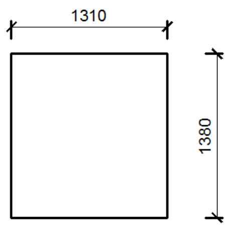
In order to create a database, forms were filled with data on buildings which were later used in seismic damage and loss evaluation calculation.

The data collection form for these buildings considered the attributes given by the Global Earthquake Model (GEM) building typology (Brzev *et al.* 2013), which describes the building using 13 properties: direction, material of the lateral load-resisting system, lateral load-resisting system, height, date of construction or retrofit, occupation, building position within a block, shape of the building plan, structural irregularities, exterior walls, roof, floor, and foundation system-those which might affect seismic performance.

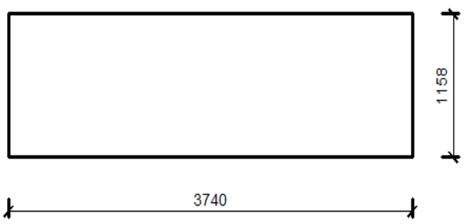
A form was created and the following data was collected for each building: address, building location data, gross area in square meters, structure type code, number of stories, story height, year of construction, type of structure and floors, structural irregularities, roof, building position within a block and shape of the building plan.

All the buildings in the database were built in the second half of the twentieth century, i.e., from 1962 to 1987.

Fig. 5 shows some of the buildings with floor plans, where different construction years and examples of regular / irregular layouts are shown.



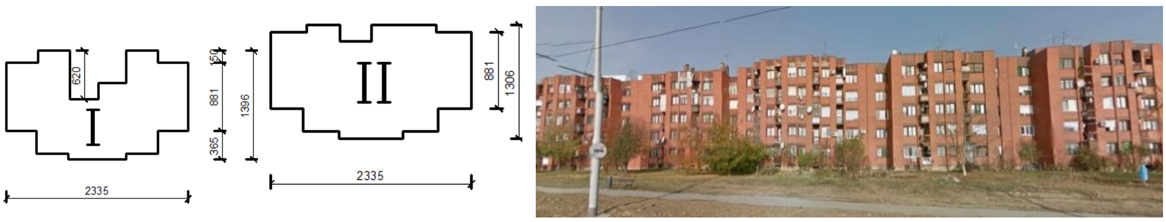
Vijenac Augusta Cesarca (1962)



Ljudevita Posavskog street (1963)

Fig. 5 Layouts (a) and fronts (b) of selected buildings from the database

Dravska street (1974)



Drinska street (1980)

Fig. 5 Continued

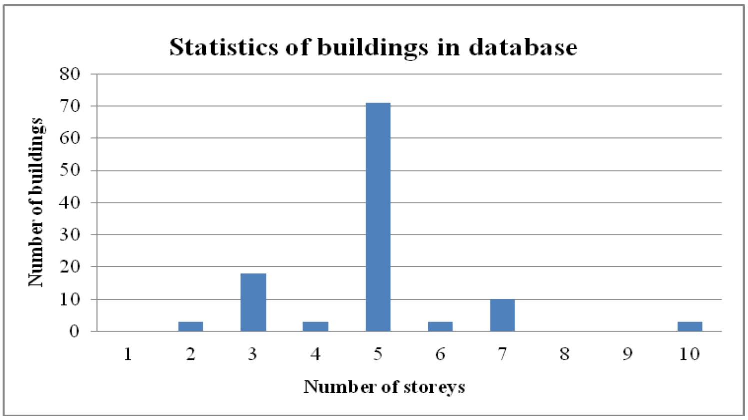


Fig. 6 Building statistics with respect to number of storeys

The database of 111 buildings consists only of confined masonry. The reason for this lies in the fact that we wanted to get adequate knowledge about the seismic vulnerability, and the impact of the construction year, the impact of the application of seismic norms, number of floors, state of conservation, etc., on the earthquake vulnerability of confined masonry. This is the dominant building typology since the late 1960's. The outer walls have a thickness 38 and 25 cm and they are made from of solid or hollow clay masonry units. Therefore, RC tie-columns are of the same dimensions as walls, e.g., 38×38 cm or 25×25 cm. According to the available project documentation of the buildings, RC tie-columns are with longitudinal reinforcement by experience, i.e., one bar in each corner. The inner walls have a thickness of 25, 12 and 7 cm, and are also made of solid bricks or hollow blocks. Residential buildings from the database built, from the 60s to about the 80s, are mainly constructed with solid clay masonry units. Later, the characteristic construction is with clay masonry units, which is also dominant today in confined masonry construction. Roof structures are either the flat roof, or a gabled roof: wooden structure with a light filling and cover of asbestos or tiles.

The floor constructions are built as semi prefabricated elements or as reinforced concrete (RC) floors. RC floors were used slightly more often during the other half of the ’70-s. The number of stories in the database varied from 2 to 10 floors (Fig. 6). Most of the buildings, 63.96%, have 5 floors. Floor heights vary from 2.5 to 2.9 m, with most of the buildings in the database having a story height of 2.8 m.

4. Earthquake vulnerability assessment method

The appraisal of the physical seismic vulnerability of structures can be conducted by using: qualitative descriptors (low, medium, high, etc. or A, B, C, etc.) like in certain macroseismic scales (Grünthal 1998), physical vulnerability indices like in the Vulnerability Index Method (VIM) or capacity curves (Milutinoviç and Trendafiloski 2003). Damage probability matrices, vulnerability functions and fragility curves may be used to acquire the expected physical damage. It is noteworthy that vulnerability and fragility curves permit the damage characterization of a structure for all earthquake intensities, while damage probability matrices correspond to a concrete point of the fragility curves (Barbat *et al.* 2010).

In this article, the macroseismic method is described and the vulnerability index and damage functions methodology from the works of Bernardini (2000) and Giovinazzi (2005) are adopted. In this method, the value of the vulnerability index can be changed depending on the structural systems, quality of construction, etc., by introducing behavior and regional modifiers which are based on expert judgments.

Since there is no available data of damaged buildings under earthquake loading in our country, we will propose behavior and regional modifiers. The modifiers are based on values suggested by earlier works and on judgment which is based on available project documentation of the considered buildings. Dependent on the proposed modifiers, the seismic vulnerability of existing buildings in the city of Osijek will be assessed.

4.1 EMS vulnerability classes

In EMS-98 (Grünthal 1998), with the introduction of vulnerability classes, the constancy in differentiating the way in which structures react to earthquakes is established.

The improvement over previous scales, which only use the type of construction as an analogy of vulnerability, is an attempt to categorize seismic resistance of buildings in a way that both the type of building and other factors are taken into account (e.g., creation, state of preservation, the regularity, etc.) and the resulting vulnerability values are presented in a table.

Also, the advantages of EMS-98 are the following: the existence of transition classes (class ranges), which takes into account the influence of factors on the vulnerability values and ranges, vulnerability values that can be used to indicate the dispersion of existing knowledge, and the representation of the probability of expectations using simplified graphical elements.

There are numerous building types for masonry structures which EMS-98 differentiates: rubble stone, adobe, simple stone, massive stone, and two types of unreinforced structures: those with manufactured stone units and RC floors as well as reinforced or confined masonry structures. With regard to RC buildings, EMS-98 draws a distinction between frame and wall systems with different degree of earthquake resistance design (ERD), which assume that buildings in an earthquake zone are designed and built for an earthquake of specified intensity, and matching site and soil conditions of the respective zone (Grünthal 1998). The different design levels suggest different levels of ground motion or base shear coefficient (Schwarz *et al.* 2015).

Depending on the level of quality and workmanship, state of preservation, regularity and other vulnerability affecting parameters, the vulnerability class has to be assigned. Schwarz *et al*. (2015) reinterpreted the situation after the 1978 Albstadt earthquake and elaborated empirical vulnerability functions of the still existing masonry type buildings with respect to the composition of building types, their construction and age, the observed behavior and damage. Under investigation were two and three storied unreinforced masonry buildings (URM): with floors of timber beam constructions and with RC floors. They concluded that, based on the EMS-98 vulnerability table, the observed shaking effects with respect to quality and quantity of damage cases (I_{obs}) refer to a calculation value of intensity I_{EMS}=7.0 to 7.25, which is lower than that one given in recent earthquake catalogues (VII-VIII). In other words, their main conclusion was that the resistance of the masonry buildings is underestimated by the assigned vulnerability classes (Schwarz *et al*. 2015). They also concluded that the results can be transferred to unreinforced masonry buildings in countries with similar construction tradition.

Therefore, based on their conclusion, and the fact that the EMS-98 table values of vulnerability are underestimated for safety reasons, we allocated a vulnerability class to our buildings. Considering the most probable vulnerability class for confined masonry is D, but, taking into account buildings with 7 to 10 stories (Fig. 6), we consider/assume that such buildings have reduced seismic resistance.

We attempt to solve this problem using the vulnerability index method, which is explained in the following section, and with which we tried to take into account behavior and regional vulnerability factors, in order to attain a better assessment of seismic vulnerability values.

4.2 Vulnerability index method

The vulnerability index method (VIM) is based on the statistical connection between the macroseismic intensity and the apparent or observed damage which were observed from previous earthquakes and the fact that various structural classes tend to encounter identical damage types (Giovinazzi and Lagomarsino 2004). The Italian National Group for Defence from Earthquakes, also known as GNDT, has been developing this methodology for the past twenty years (Corsanego and Petrini 1994). The methodology has been enforced and adjusted through the years both to validate results and present improvements (Benedetti and Petrini 1984, Bernardini 2000, Giovinazzi 2005).

VIM uses the collected information and parameters which influence the building vulnerability (plan, type of foundation, structural and non-structural elements, type and quality of materials). The method is called ‘indirect’ because through the vulnerability index, which was acquired by combining data from different building typologies in a specific area collected by observation in situ, the relation between seismic action and the response is obtained. While the seismic action is defined in terms of macroseismic intensity, the building’s seismic quality has to be described by means of a vulnerability index. Structural typology, age and other related characteristics (regularity, position, etc.) of the buildings were taken into consideration.

To perform the vulnerability evaluation for each building, we followed the VIM as proposed by

Milutinovic and Trendafiloski (2003). The EMS-98 vulnerability approach was also used in order to assist with the interpretation of results.

The first step was to define a building typology and then assign average vulnerability indices to the vulnerability classes (Milutinovic and Trendafiloski 2003). As part of the Project Risk-UE, Milutinovic and Trendafiloski (2003) defined 23 building classes: 10 classes for masonry (M), 7 for reinforced concrete (RC), 5 for steel (S) and 1 for wooden (W) buildings. The representative values of vulnerability indices for the building typology found in our database have been defined (Table 1): the most plausible value for the specific building type V_I^* (the typological vulnerability index) is computed as the centroid of the membership function; V_I^- and V_I^+ are evaluated by a 0.5-cut of the membership function, representing the bounds of the plausibility range of V_I^*; $V_{\min}$ and $V_{\max}$ correspond to the upper and lower bounds of the possible values of the final vulnerability index value, for the specific building type.

The vulnerability index of every building depends on the behavior of its structural system and it involves other modifiers as follows (Giovinazzi 2005)

$$V_I = V_I^* + V_r + V_m \tag{3}$$

where V_r is the regional vulnerability modifier and $V_{m,}$ is the behavior modifier.

An analytic expression is defined for the operational implementation of the methodology; accordingly the mean damage grade μ_D is defined as a function of the macroseismic intensity I and depends on two parameters: the vulnerability index V_I and the ductility index Q (Giovinazzi 2005)

$$\mu_D = 2.5\left[1 + tanh\left(\frac{I + 6.25 \times V_I - 13.1}{Q}\right)\right], \tag{4}$$

where:

I - the macroseismic intensity,

V_I - the vulnerability index,

Q - the ductility index; it controls the slope of the curves and assumes different values to fit the data obtained through damage surveys; for residential buildings, the proposed value is 2.3 (Giovinazzi 2005).

Based on this, damage probability matrices can easily be obtained by assuming that the damage

Table 1 Vulnerability index values for confined masonry wall (Milutinovic and Trendafiloski 2003)

Typology		**Description**	**Vulnerability indices**				
			V_{Imin}	V_I^-	V_I^*	V_I^+	V_{Imax}
Masonry	M4	Reinforced or confined masonry walls	0.14	0.33	0.451	0.633	0.70

Table 2 Damage states and mean damage index values (Barbat *et al.* 2010)

Most probable damage state	**Mean damage index intervals**
No damage	0-0.5
Slight damage	0.5-1.5
Moderate damage	1.5-2.5
Extensive damage	2.5-3.5
Complete Damage	3.5-4.0

probability follows a binomial or beta-equivalent probability distribution (Giovinazzi and Lagomarsino 2004, Barbat *et al.* 2010).

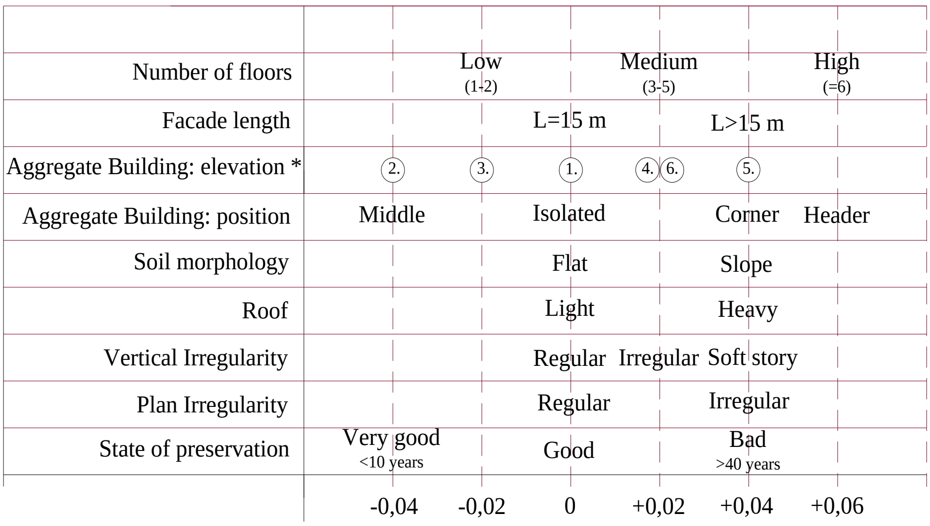
Table 2 shows the most probable damage grade as a function of this average damage index that allows expressing seismic damage scenarios by using a single parameter.

4.2.1 Regional and behavior modifiers

The identification of behavior modifiers was made empirically, on the basis of the observed typical damage pattern, taking into account also what was suggested by several Inspection Forms (Benedetti *et al.* 1988) and by the previous proposal of Coburn and Spence (1992). The modifying scores are attributed on the basis of expert judgment although they have been partially calibrated by comparison with previous vulnerability evaluations (Giovinazzi and Lagomarsino 2004).

Since there are no available data of damaged buildings under earthquake loading in our country, we propose behavior modifiers based on values suggested by earlier works of Milutinovic and Trendafiloski (2003) and Lantada *et al*. (2010) and on judgment based on available project documentation of the considered buildings.

Behavior modifier factors V_m are adopted according to the proposal of Milutinovic and Trendafiloski (2003) and extended with Lantada *et al*. (2010), who introduced modifiers related to plan irregularity and height in relation with adjacent buildings and façade length. A description of the behavior modifiers used in this study for masonry typologies in presented in Table 3. The behavior modifiers are divided into nine categories. The total behavior modifier for a single building is the sum of the individual values for these nine categories. The only difference is that for Aggregate building position we used the same values for corner and header buildings (+0.04). Isolated building blocks consisted of two or three connected buildings and make up more than half



* 1. Adjacent buildings at same level, 2. Adjacent buildings higher, 3. An adjacent building higher and the other at same level, 4. An adjacent building lower and the other at same level, 5. Adjacent buildings lower,6.An adjacent building lower and the other higher

Fig. 7 Behavior modifiers according to Milutinovic and Trendafiloski (2003) and extended with Lantada *et al*. (2010)

of the database. Therefore, for a block of two buildings, the behavior modifier for both was assumed to have a value of +0.04. For blocks of three buildings, the behavior modifier for building in the middle was 0.00, while the neighboring buildings were +0.04. The modifier - façade length - was considered only for masonry buildings. The values of behavior modifiers are shown in Fig. 7.

A regional vulnerability factor V_r takes into account building typologies at a regional level. It means that it affects vulnerability due to traditional constructive techniques in different regions. The range boundaries are quite large in order to be representative of the huge constructive technique varieties used in different European Countries. Regional vulnerability factor V_r is allowed to modify the V_I^* typological vulnerability index on the basis of expert judgment or on the basis of historical data that are available. An expert judgment must be the result of: precise technological, structural, constructive information of better or worse average behavior with regard to the one which is proposed. When there is data of observed damage; the average curve may be shifted in order to obtain a better approximation of the same data.

Oliveira and Mendes Victor (1984) proposed the value of V_r=0.12 for Massive Stone typology in Lisbon that could provide a better behavior than the proposed average one.

Feriche *et al*. (2008) proposed the values of the regional vulnerability factor between 0.08 to 0.16 from the analysis of damaged buildings after the Lorca 2011 earthquake, depending on the years of seismic codes and structural types.

Also, regional vulnerability factors for masonry buildings for masonry types built of simple stone (M3M) are proposed with a value of 0.25, for pre-code low rise and mid-rise masonry buildings with RC floors (M6LPC and M6LMC) 0.15 and 0.12 respectively and for RC buildings 0 (Tsereteli *et al.* 2014).

We adopted the regional modifiers according to the work of Tsereteli *et al.* (2014) with the value of 0 for RC buildings and, according to Ferriche *et al*. (2008) the value of 0.08 for confined masonry.

Table 3 Vulnerability index values for the vulnerability classes defined in EMS-98 (Giovinazzi 2005)

Class	V_{Imin}	V_I^-	V_I^*	V_I^+	V_{Imax}
A	0.78	0.86	0.90	0.94	1.02
B	0.62	0.70	0.74	0.78	0.86
C	0.46	0.54	0.58	0.62	0.70
D	0.30	0.38	0.42	0.46	0.54
E	0.14	0.22	0.26	0.30	0.38
F	-1.02	0.06	0.10	0.14	0.22

Table 4 Relation between V_I^* and EMS98 classes (Martinez-Cuevas and Gaspar-Escribano 2016)

V_I^*values	EMS-98 class
>0.82	A
0.66 - 0.82	B
0.50 - 0.66	C
0.34 - 0.50	D
0.18 - 0.34	E
<0.18	F

4.2.2 Translation to the EMS-98 vulnerability classes

It is convenient to translate the V_I estimates obtained so far into the vulnerability classes defined in the EMS-98, as most damage reports and vulnerability assessment are more easily compared using this scale (Table 3). Each vulnerability assessment method models the damage on a discrete damage scale; a frequently used example is the European Macroseismic Scale (EMS-98). The damage scale is used in order to produce post-earthquake damage statistics in empirical vulnerability procedure or is related to limit-state mechanical properties of the buildings.

For each building, the mean damage grade was calculated based on the V_I values. Each V_I value was calculated by summing all the behavior modifiers and regional modifier. Then the average V_I value is obtained. The vulnerability indices V_I are related to EMS-98 vulnerability class using Table 4 obtained by modifying the values from Milutinovic and Trendafiloski (2003). This relationship was presented in the work of Martinez-Cuevas and Gaspar-Escribano (2016).

5. Results

For all confined masonry buildings, we first calculated the average behavior modifier factor. As it was already mentioned, regarding the behavior modifier V_m, this work basically follows the approach of Milutinovic and Trendafiloski (2003) extended with the work of Lantada *et al*. (2010). For example, buildings with a bad state of conservation, located at the header of the block and with more than 6 stories present high V_m values, whilst isolated medium height buildings have lower V_m values.

We calculated the average behavior modifier factor using the summed behavior modifier factors for each building. Based on the statistics of 111 confined masonry buildings, the average behavior modifier factor was 0.12.

We adopted the regional modifiers V_r according to Ferriche *et al*. (2008) with the value of 0.08 for confined masonry.

Thus, if we apply the modifiers, which are shown in Fig. 8, 47 confined masonry buildings (42.34%), instead of vulnerability class D, are now vulnerability class C, and even 64 buildings (57.66%) become vulnerability class B. It can be highlighted that the modifier factors can drastically influence the corresponding vulnerability class. It can also be concluded that the values of modifiers consequently have a high impact on the earthquake vulnerability assessment.

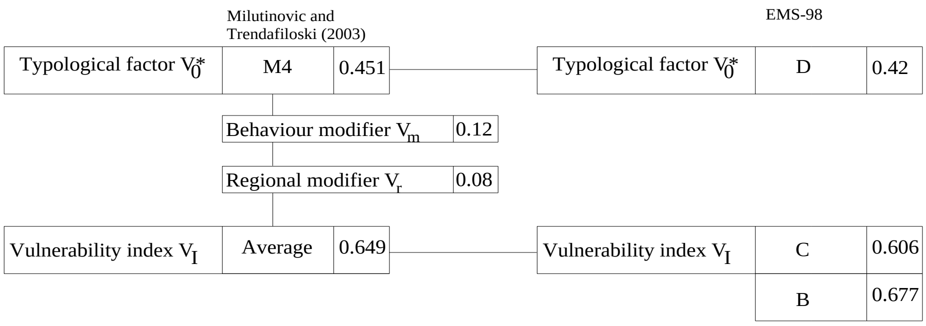


Fig. 8 Applied modifiers factors and corresponding vulnerability classes according to EMS-98

This impact of the behavior and regional modifiers on the V_I values, e.g., on the mean damage grade is presented in Fig. 9. Four separate estimates are provided, resulting from the different approaches used to estimate the V_I values: The first one considers mean damage grade calculated using only the typological V_I^* value (blue) for the M4 building typology, the second one considers the typological V_I^* value (red) for the corresponding building class according to EMS-98 (D), while the last two values consider all behavior modifiers - first (green) calculated for M4 typology and second one (violet) for the corresponding class according to EMS-98 (obtained by using Tables 3 and 4).

For vulnerability class C, an average vulnerability index value of 0.6055 is obtained, while an average vulnerability index value of 0.6804 is obtained for 64 buildings having vulnerability class B.

The mean damage grades expected in confined masonry and RC buildings for three levels of intensity (VI, VII and IX) are calculated using Eq. (2) and the results are presented in Table 5.

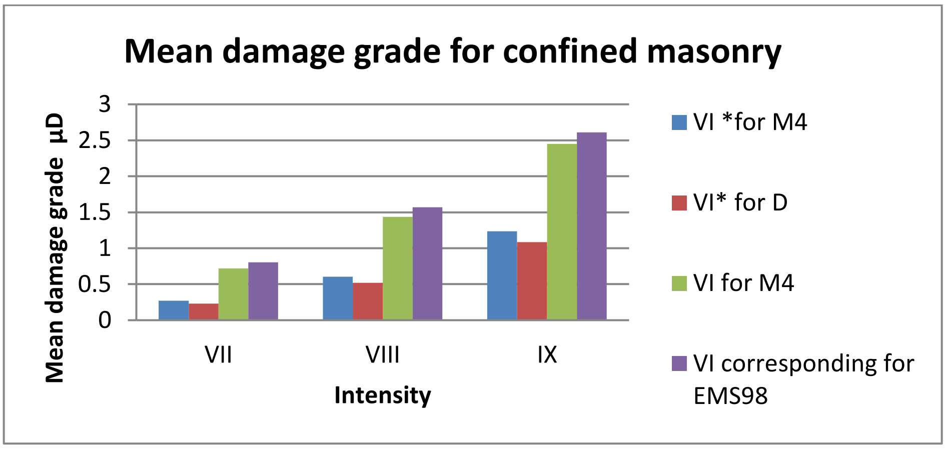


Fig. 9 Mean damage grade calculated for confined masonry buildings

Table 5 Average values of mean damage grades for three levels of intensity

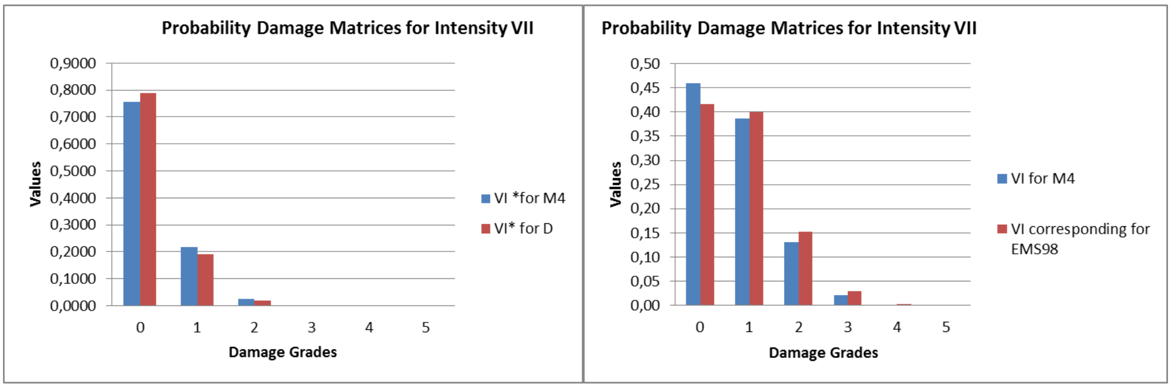
Intensity	Average μ_D for confined masonry	
	M4	**EMS-98**
VII	0.722	0.805
VIII	1.436	1.570
IX	2.450	2.610

Table 6 Average values of mean damage grades for three levels of intensity according to EMS-98

Intensity	Confined masonry	
	Vulnerability class B	**Vulnerability class C**
VII	0.846	0.592
VIII	1.633	1.211
IX	2.679	2.159

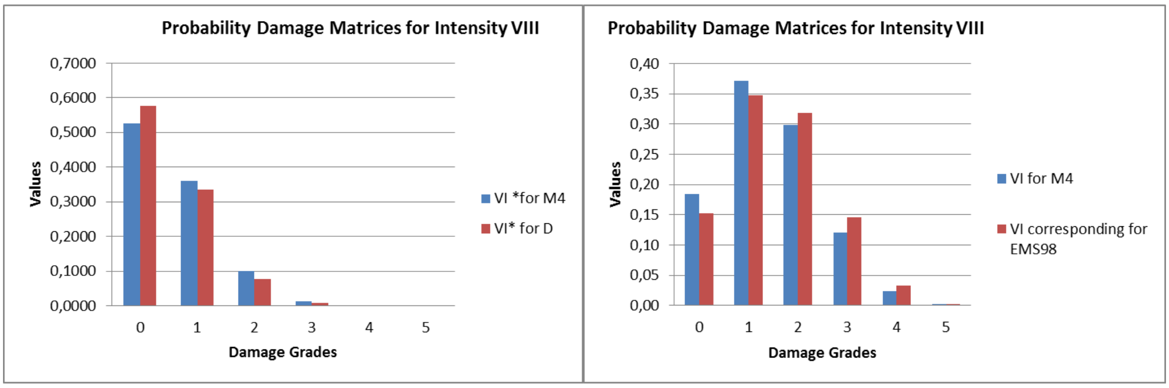
It can be noticed that confined masonry has a lower seismic resistance when the mean damage grade is related to the probable damage grade. For earthquake intensity VIII, it can be seen that minor to moderate damage can be expected to be observed in these buildings. Likewise, for intensity IX even considerable damage may be expected. Calculation results for confined masonry are further presented for two classes according to EMS-98 (vulnerability classes B and C), which are given in Table 6, to get insight in differences between average mean damage grade according to Milutinovic and Trendafiloski (2003) and with corresponding values for EMS-98 (Grünthal 1998).

When applying regional behavior modifiers, it was observed that the reduction of vulnerability class values by two classes, for more than half of the considered building, displays a reflection of the real situation of these buildings and realistically reflects the derived vulnerability class. Most of these buildings are older than 40 years and the buildings with more than five floors have drastically reduced seismic resistance, as opposed to the current regulations EN 1996-1-1 (CEN 2005).



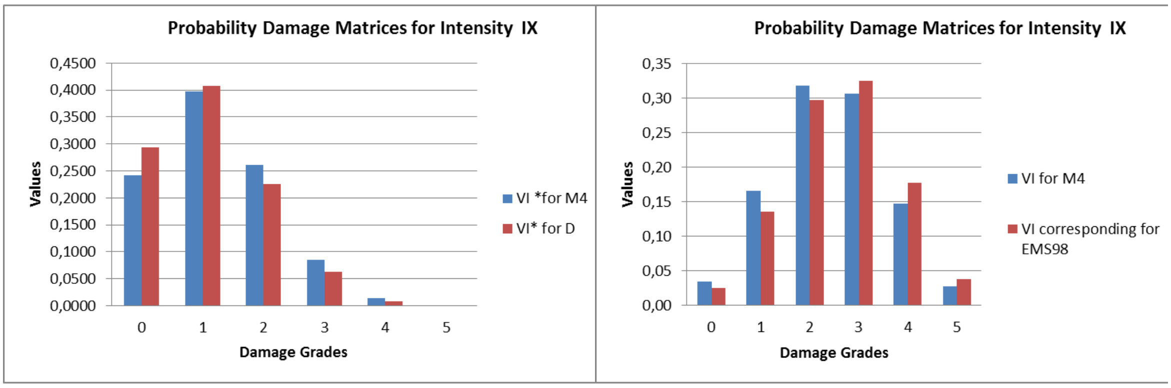
(a) (b)

Fig. 10 Damage probability matrices for confined masonry for VII level of earthquake intensity: (a) using typological values (V_I^*), (b) using Vulnerability index with added modifiers (V_I)



(a) (b)

Fig. 11 Damage probability matrices for confined masonry for VIII level of earthquake intensity: (a) using typological values (V_I^*), (b) using Vulnerability index with added modifiers (V_I)



(a) (b)

Fig. 12 Damage probability matrices for confined masonry for IX level of earthquake intensity: (a) using typological values (V_I^*), (b) using Vulnerability index with added modifiers (V_I)

Table 7 Percentage of buildings with different damage grades for three intensity level for class B

Intensity		**VII**		**VIII**		**IX**	
Class	**Damage grade**	% of buildings	Quantity EMS-98	% of buildings	Quantity EMS-98	% of buildings	Quantity EMS-98
	1	40.30%	Many	33.58%	Many	12.43%	A few
	2	16.41%	A few	32.57%	Many	28.71%	Many
B	3	3.34%	A few	15.80%	A few	33.15%	Many
	4	0.34%	None	3.83%	A few	19.14%	Many
	5	0.01%	None	0.37%	None	4.42%	A few

Table 8 Percentage of buildings with different damage grades for three intensity level for class C

Intensity		**VII**		**VIII**		**IX**	
Class	**Damage grade**	% of buildings	Quantity EMS-98	% of buildings	Quantity EMS-98	% of buildings	Quantity EMS-98
	1	35.78%	Many	39.92%	Many	22.47%	Many
	2	9.2%	A few	25.55%	Many	34.20%	Many
C	3	1.29%	A few	8.18%	A few	26.02%	Many
	4	0.09%	None	1.31%	A few	9.90%	A few
	5	0.00%	None	0.08%	None	1.51%	A few

Damage probability matrices are obtained using the calculated mean damage grades. First, they were calculated using typological values of vulnerability indices (Figs. 10(a), 11(a), 12(a)) and then using vulnerability indices with added modifiers (Figs. 10(b), 11(b) and 12(b)), for three levels of intensity: VII, VII and IX, respectively. The impact of the modifiers is also shown.

A significant increase in the modifier implies a general shift of buildings toward higher vulnerability classes. The analysis is then focused in the damage distribution of these vulnerability classes. Therefore, in Tables 7 and 8, the results are presented in the form of quantities and vulnerability classes according to EMS-98, where the mean damage grades are calculated according to Milutinovic and Trendafiloski (2003). The quantities are determined using ranges as suggested in Grünthal (1998): few, many and most are defined as three contiguous ranges of percentages (e.g., 0-20%, 20-60%, 60-100%).

The impact modifier is significant in: the final value of vulnerability coefficient, the final vulnerability class, and in the values in the damage probability matrix. In the vulnerability table, according to EMS-98, for the same vulnerability class, the probable vulnerability class is given, but dispersion is possible depending on the degree of earthquake resistance. This means that, assigning a lower or higher vulnerability class highly depends on the expertise of the person who assesses the building. Using VIM method, it was easier to determine the type of structure, to assign a typological index of vulnerability, and then, depending on the 9 descriptions of modifier factors, get a final vulnerability class. Modifiers are largely used to connect vulnerability classes which were obtained by the VIM method and the EMS-98 method, especially if there is insufficient experience in the assessment of the behavior of buildings.

6. Conclusions

In this study, we used the macroseismic approach as proposed by Milutinovic and Trendafiloski (2003) and Giovinazzi (2005) in order to provide the vulnerability evaluation for each of the 111 buildings within Osijek's area. For this method, structural typology, age and other characteristics (regularity, position, etc.) of the buildings were considered. Vulnerability indices were acquired by using typological values for every structural system and adding both regional and behavior modifiers. On account of there not being available data of damaged buildings under earthquake loading in our country, we are proposing behavior modifiers based on values suggested by former works and on judgment based on available project documentation of the considered buildings. Since most damage reports and vulnerability assessment are easily compared using EMS-98, we translated the V_I estimates obtained into the vulnerability classes defined by EMS-98. It can be concluded that the regional and behavior vulnerability modifiers affect the average value V_I so much that the vulnerability class is expanded by one or two classes. According to EMS-98, the most vulnerable class for confined masonry is vulnerability class D, but by adding regional and behavior modifiers, 42.34% of confined masonry buildings become vulnerability class C, and even 64 buildings (57.66%) become vulnerability class B. Then, based on vulnerability indices the mean damage grade was calculated for each building. Using the calculated mean damage grades, the damage probability matrices are obtained for VI, VII and IX levels of earthquake intensity.

Acknowledgments

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