ORIGINAL RESEARCH

Seismic vulnerability assessment of masonry buildings in Banja Luka and Sarajevo (Bosnia and Herzegovina) using the macroseismic model

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Abstract

Assessment of seismic vulnerability in urban areas is a challenging task that requires a meticulous and systematic approach. Sarajevo and Banja Luka, together with Tuzla, are the most urbanized and densely populated cities in Bosnia and Herzegovina. Sarajevo and Banja Luka experienced devastating earthquakes in 1962 and 1969, respectively. This is why it is of the utmost importance to conduct seismic vulnerability evaluation of the existing building stock in Bosnia and Herzegovina. Until today no systematic database regarding structures and their typology has been compiled for the territory of Bosnia and Herzegovina in connection with their vulnerability to seismic actions. The choice of an appropriate vulnerability method plays a key role in the process of assessment of seismic risk and highly depends on the available information, characteristics of the buildings, organization of data collection and decision-makers. Among various methods, it was decided to use the macroseismic method derived from the EMS-98 scale for the vulnerability assessment of the existing buildings in Bosnia and Herzegovina. The database was obtained from the "typology of residential buildings in the BiH" project, a comprehensive survey of 13,044 existing residential buildings in BIH, which was conducted for energy performance assessment of the national building stock. For the purpose of this research, the database was reduced to a sample of 2933 buildings, as it included a selection of only unreinforced and confined masonry buildings built from 1918 to 2014 and located in Sarajevo and Banja Luka. The aim of this paper is to provide an overture in assessing the seismic risk in Sarajevo and Banja Luka by applying the method based on the vulnerability index. The vulnerability index is calculated by the macroseismic method which is in the function of the type of building, regional vulnerability factor and behavior modifier factors. The application of this method confirms the notable seismic risk in the cities of Sarajevo and Banja Luka due to the high vulnerability of the buildings. It may be argued that the behavior modifiers which had the largest impact on the change of the vulnerability class were the number of floors and type of roof structure. This research intends to contribute to the prevention of an earthquake disaster, in the form of a theoretical forecast of the aftermath: structural damage and/or socio-economic losses that may occur after an earthquake.

Keywords URM buildings · Vulnerability index · Bosnia and Herzegovina · Seismic assessment · Macroseismic method

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1 Introduction

Bosnia and Herzegovina (BIH) is a country located in the center of the South-Eastern Europe (SEE) region. As per Euro Mediterranean Seismic Hazard Map, the territory of BIH falls into moderate seismic hazard having the PGA in the range of 0.08 to 0.24 g, while the south-western part of the country experiences a high hazard (PGA > 0.24 g) (Reinecker et al. 2003). High seismic prone zone (PGA > 0.24 g) is mainly located in the southern Herzegovina occupied by 9.8% of the total population of BIH and covering 16.3% of the total area of BIH. A little less than 90% (3,154,134 citizens) of the population of BIH can experience moderate earthquake ground motion with PGA up to 0.24 g covering 83.2% of the territory of BIH. Less than 1% of the population living in 0.5% of the entire territory of BIH can experience earthquakes having a PGA smaller than 0.8 g (BAS 2018). The most devastating earthquake which hit Bosnia and Herzegovina was the 1969 Banja Luka 6.4 magnitude earthquake according to Richter's scale. Seven years earlier, in 1962, Sarajevo was hit by a strong 6.0 magnitude by Richter's scale earthquake with the epicenter in Mount Treskavica hill, located about 30 km south of downtown Sarajevo. At the epicenter, the intensity of this earthquake was VIII, and in the city center VII degrees according to Mercalli–Cancani–Sieberg (MCS) scale. In the last few years, the territory of BIH was hit by several earthquakes of magnitude 4 by Richter's scale or higher. Luckily, no casualties or higher degree of devastation were recorded, however, this opened many new discussions among different researchers, scientists, seismologists, and engineers. As far as the authors are aware, very limited data is available to assess the seismic vulnerability of the existing buildings stock in Bosnia and Herzegovina, leading to a few studies in this field conducted by individual researchers (Ademović 2011; Ademović et al. 2013, 2019). Currently, in Bosnia and Herzegovina, there is a lack of a well-organized and efficient database of buildings and their typologies on the basis of which a vulnerability seismic assessment could be performed.

The present paper expounds the results of the preliminary study of the seismic vulnerability and possible damage to single-family houses and residential housing located in the cities of Sarajevo and Banja Luka, based on the previously formulated database created throughout the research on the correlation of the typology of residential buildings and their energy efficiency (Arnautovic-Aksic 2016). The main goal of this article is to determine the effect of the modifiers on the overall vulnerability index and to determine the influence of the construction year, the application of seismic norms, the number of floors, state of conservation, etc., on the earthquake vulnerability of unreinforced masonry (URM) and confined masonry buildings. For this reason, the vulnerability index method (VIM) was solely applied to the selected masonry buildings in the city of Banja Luka and Sarajevo. Since a similar study has not yet been carried out for the Bosnia and Herzegovina area, we believe that the building database for the two cities will be of great importance, as well as the preliminary results of the building's vulnerability from the database due to earthquake action.

In order to assess the seismic risk of an urban area, it is necessary to elaborate three aspects of the problem: (a) define the seismic hazard, (b) create a database consisting of types of buildings with regard to their construction features, function, occupancy, and their role immediately after the earthquake, (c) perform the assessment of fragility and vulnerability using the created database by applying an appropriate method (empirical, analytical and expert judgment or their combination). The above-mentioned measures

are intended to estimate the potential risk for residents and property in the case of earthquake ground motion.

1.1 Vulnerability assessment methods

The seismic vulnerability of existing buildings can be assessed by several methods. Basically, these methods can be grouped into three major groups depending on the nature and objective of the study, available information, characteristics of the buildings, organization of data collection and decision-makers (Preciado et al. 2015; Porter et al. 2012). The empirical methods are based on statistical observation of the damage of the buildings caused by previous earthquakes, while the analytical methods consist of simulations of buildings' performance, represented by a numerical model. The advantage of empirical methods is manifested in the fact that they are based on real data, meaning that they take into account different effects like soil-structure interaction, topographic and lithographic effects of the construction site, as well as the variability in the bearing capacity of a group of buildings. However, this can also be a disadvantage because fragility curves obtained in this manner are specific to a given area, with particular site impact conditions, earthquake parameters (magnitude, depth, etc.) and bearing capacity of the building. The reliability of empirical fragility or vulnerability functions is highly dependent on the quality of available data, which may be disputed in case of limited or poor-quality data. At the moment, at least 119 empirical fragility curves have been published (Rossetto et al. 2013). Maqsood et al. (2016) used the GEM empirical vulnerability assessment guidelines created by Rossetto et al. (2014) for the development of the vulnerability functions and identification of optimum functions. In the study, a large loss database consisting of 14,000 insurance claims in Newcastle and 400 surveyed unreinforced masonry (URM) and timber frame buildings was used with the aim to develop vulnerability functions for these types of buildings. Usually, the data which is available is based on events of low magnitudes with limited damage, leading to fragility curves that may be untrustworthy assuming higher intensities. Through a series of experiments Ioannou et al. (2015) studied the impact of ground-motion variability and uncertainty on empirical fragility curves. As well, undamaged buildings were inappropriately considered in the survey. All this leads to uncertainty about the number of all elements that are exposed to the event. Finally, another difficulty lies in the lack of knowledge of the exact movement of the ground in the strict vicinity of the damaged buildings. In this case, the estimate is done with a macroseismic intensity (a conversion that is affected by extreme high heterogeneity) or through the extrapolation of recorded signals from nearby stations. If the macroseismic intensity is used in the empirical approach several uncertainties arise. First of all, the intensity is a subjective parameter mainly based on damage observations and individual expert impressions. Secondly, the effects of soil and site conditions cannot be quantified in a clear manner (Grünthal 1998). Formulation of Intensity-based Damage Probability Matrices is based mainly on damage observations from past earthquakes and its application for future earthquakes is questionable (Crowley et al. 2004).

The analytic approach is based on the engineering principles for the estimation of damage or loss. The final result of this approach is the creation of fragility curves, which express the probability that the damage sustained by a building/class of buildings for a given intensity level will reach or exceed a given state (Maqsood et al. 2016). The first step in this approach is the creation of a finite element model of a representative individual building or class of buildings in the selected software. Once this is done the response of the

building to earthquake motion with respect to the seismic hazard is analyzed by the application of a selected nonlinear analysis type, damage model and damage threshold criteria (Calvi et al. 2006). In this procedure, the application of pushover analysis (D'Ayala et al. 2015) is required which may be challenging for non-engineering structures, if not impossible. Additionally, this analysis is limited only to building typologies whose response is dominated by the first natural mode. The reliability of the model depends on the available information, which is usually insufficient for a larger building stock, thus leading to uncertainties. In order to produce the capacity curves and fragility curves, it is necessary to generate a set of building models with varying geometry and material parameters, which will inevitably be affected by the uncertainties and assumptions incorporated already in the models (Crowley et al. 2004). Additionally, the level of detail of the building classification has a strong impact on the derived capacity curves and fragility functions. Narrowing down a building class by geometrical features, height, number of stories, etc., will ensure higher representativeness of the mean fragility parameters. Unlike the empirical methods, this is a more detailed analysis, in which the vulnerability assessment algorithms have a direct physical meaning, allowing a straightforward calibration to various characteristics of building stock and hazard. One of the benefits is the applicability of this method in regions of low seismicity which have experienced very little or no damage at all. Though it is a very time consuming and computationally intensive procedure, the models developed in this manner are not dependent on the region, and their applicability is global if appropriate sensitivity analysis and calibration are carried out (D'Ayala and Meslem 2012).

Expert judgment needs to be incorporated in both of these groups of methods to some extent, as certain assumptions require expert opinion and proposals. However, in some cases, expert judgment will be a reliable source to assess the building vulnerability of particular building types. This approach has been adopted in cases where there is no available or rather limited data on past earthquake damage required to derive empirical vulnerability functions, or in situations when the cost and time for the derivation of analytical vulnerability functions are too high. The success of any expert elicitation process is highly reliant on how carefully the experts are chosen, whether the experts provide unbiased decisions, and, finally, how multiple opinions are harmonized or combined (Jaiswal et al. 2012). The most commonly used methods of expert elicitation and synthesizing expert judgments are the Delphi method and Cooke's method. Estimating structural collapse fragility for selected generic building typologies using expert judgment with the application of Cooke's method was for the first time done by Jaiswal et al. (2014). The result of this research was the creation of twelve fragility curves for common generic construction types. However, in order to obtain the inputs from the experts in a successful manner, substantial effort was required.

Each approach has its pros and cons (Kwon and Elnashai 2006). It is the quality of the attained data, the available resources, expertise of the analyst, and the level of assessment which determines which approach(es) will be used. A simplified approach is used in index-based methods, in which the main building type properties are used to acquire a score that is related to seismic vulnerability by applying relationships obtained from different sources (empirical, analytical, expert judgment, or a combination). The employed analytical and empirical data which are used as input in each index method need to be able to reflect different damage states of the assessed building. In the index-based methods, the priority is given to the input data which are seen as authors' assumption of the significance of different building properties for conducting a vulnerability assessment.

Vulnerability index method (VIM) is taking into account five non-null damage states, which expresses the seismic action in terms of macroseismic intensity and the seismic quality of the building by means of a vulnerability index (Lantada et al. 2009). Vulnerability

index is obtained by a combination of data from different building typologies in a specific area collected by in situ observation. 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 the behavior and regional modifiers which are based on expert judgments (Hadzima-Nyarko et al. 2016). This means that the relationship between seismic action and the response is done in an indirect manner through the vulnerability index. Semi-empirical functions are used for the measurement of the damage degree. A building typology index and set of behavior modifiers are used in the vulnerability index method. The building typology index is determined by the application of the probability of damage which was formerly connected with the EMS-98 classes. The modifiers have been derived for reinforced concrete (RC) and masonry structures (Milutinovic and Trendafiloski 2003; Lantada et al. 2010). Information that is usually covered by the modifiers refers to the floor, roof, and foundation elements, the number of levels, type of structural system, level of earthquake-resistant design, irregularities in the plan, elevation, and mass, position of the building in a block, other general seismic weaknesses, etc. Giovinazzi and Lagomarsino (2004) used a fuzzy set theory for the derivation of damage probability matrices and functions relating damage to seismic intensity (given EMS-98), generating a vulnerability index valid to European buildings.

Which method should be and could be used in the vulnerability assessment depends on the availability of data and has to take into account criteria suitable to the specific characteristics of an area and based on that, the decision shall be made (Preciado et al. 2015). The analytical approach is used for individual buildings or classes of buildings. While acknowledging the benefits of the analytical method, this research was conducted using the vulnerability index method as the most suitable, because it specifically focuses on the distinctive characteristics of each building.

1.2 Types of taxonomies-database

Residential and commercial building stock is usually taken into account in the seismic assessment as exposure assets. Some degree of building data, its characteristics, have to be known regardless of the method applied. A building inventory is a catalogue of the buildings and facilities in each class of taxonomy, used in loss models to define the exposure to a specific hazard, based on insurance exposure (Bevington et al. 2012). Generally, two types of taxonomies could be employed, either specific risk-oriented taxonomies or faceted taxonomies (Pittore et al. 2018), which have been recently developed.

In risk-oriented taxonomies, sets of typological classes that have similar structural characteristics are used. Buildings of a certain class will manifest similar seismic performance. Different regions developed different risk-oriented taxonomies however their application has been used in areas where macroseismic data had been available. In the USA the HAZUS-MH taxonomy (Kircher et al. 2006, FEMA 2006) and the ATC-14 (1987) were widely used. Prominent taxonomies used in Europe are European Macroseismic Scale (Grünthal 1998), RISK-UE (Mouroux et al. 2004) and PAGER-STR taxonomy which represents the most comprehensive global building database (Jaiswal et al. 2010) which found its application in the global exposure model. Usually, specific risk-oriented taxonomies are used as the input data for conducting a large-scale seismic assessment and assigning a fragility and/or vulnerability models of individual buildings. Compilation of the risk-oriented taxonomies which have been used in the development of the exposure models was a result

of either a combination of data obtained from the authorities (e.g., census data) and expert judgment (Tyagunov et al. 2004) or as a result of data obtained from investigations conducted in the field (Abrahamczyk et al. 2013). The drawback of these taxonomies is their fixation to a certain geographic region (Jaiswal et al. 2010) which was overcome by the development of faceted taxonomies. A faceted taxonomy is a set of classifications, each describing a specified domain from a different point of view (Tzitzikas, 2009). An example of such taxonomy is the GEM taxonomy (Brzev et al. 2013) developed within the SYNEG-G project. The Global Earthquake Model (GEM) typology provides a detailed description of the building consisting of 13 properties which might affect seismic performance (Brzev et al. 2013): 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. The data collection form for the buildings considered in this paper use some of the attributes given by the GEM building typology. Any taxonomy is a compromise between simplicity and thoroughness.

In this regard, the building data used in this research comes from the survey of the typology existing residential buildings conducted for the purpose of the assessment of energy efficiency performed by a team of experts from four faculties of architecture and mechanical engineering from the universities of Sarajevo and Banja Luka in collaboration with German Agency for International Cooperation (GIZ) (Arnautovic-Aksic et al. 2016). In Bosnia and Herzegovina, there is no available data of damaged buildings under earthquake actions. The attributes given by the global earthquake model (GEM) building typology which were taken into account, in this case, were: material of the lateral load-resisting system, lateral load-resisting system, height, date of construction, building position within a block, shape of the building plan, roof, and floor. In that respect, it was necessary to propose behavior modifiers based on values suggested by earlier works and on judgment based on available project documentation of the evaluated buildings in the database. The gained vulnerability index values were translated into vulnerability classes defined in EMS-98.

1.3 Seismicity of the region—seismic hazard

South-Eastern Europe (SEE) has one of the most compound tectonic formulations in Europe, and BIH is situated in the heart of this region. This part of the world has been interesting for many researchers, i.e. former Yugoslavia, northwestern Balkans, Northwest Bosnia and Herzegovina. Some researchers concentrated on the influence of deep and shallow geology and developed the uniform hazard spectra for this region (Bulajić et al. 2013; Manić et al. 2015; Lee et al. 2015).

The sixth century B.C. can be defined as the starting point of the written earthquake historical data in the Balkans. In 1882, the first instrumental earthquake record was done in the Balkans. On average, this region is annually struck by an earthquake of a 6.3 magnitude by Richter scale. In the last century, eighty destructive earthquakes struck this region (Ademović 2011). However, data regarding earthquakes in the Balkan's early history is rather poor. Up to now, the most devastating earthquakes happened outside of Europe, with certain exceptions (Lisbon 1755; Patitírion 1905; Messina 1908; Vrancea 1940; Dúrcal 1954, etc.). Figure 1 shows earthquakes of the magnitude above 5.5 in Europe from 1900 to 2016.

Recent earthquakes registered worldwide (2017 Puebla earthquake, August 2016 Central Italy earthquake, 2015 Gorkha earthquake, 2014 Ludian earthquake, 2013 Balochistan
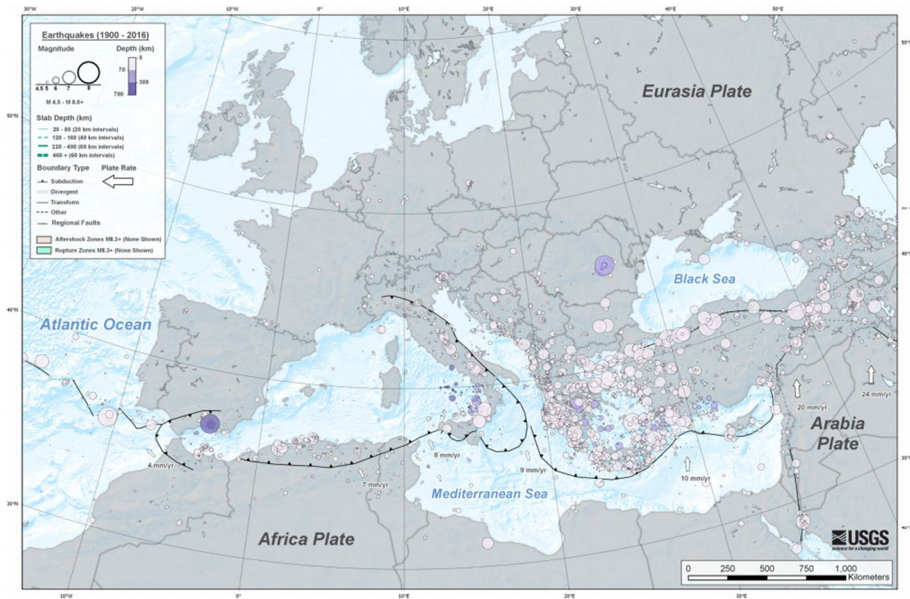
Fig. 1 Earthquakes M5.5 + (1900-2016) Europe (USGS)

earthquakes, 2012 Emilia earthquakes, 2012 Ahar earthquakes, 2011 Christchurch earthquake, 2011 Van earthquakes, 2009 L'Aquila earthquake) caused human casualties, material devastation and damages to the masonry buildings implying the need for investigation of the vulnerability of existing building stock.

The seismicity of the Balkans and Bosnia and Herzegovina is not only affected by the movement of the "big" tectonic plates, Euroasian and African plate but as well by the movement of the Arabian and micro Adriatic plate (Oldow et al. 2002). Many researchers investigated this region and offered different hypotheses regarding the creation, kinematic and the time of the creation of the Adriatic microplate: Nocquet (2001), Mele (2001) and McClusky, et al. (2000). This is still being investigated and there has been no unanimously accepted hypothesis.

Bosnia and Herzegovina is divided into three parts: area of the Outer Dinaric Alps with the most frequent earthquakes (No. 1), area of the Central Dinaric Alps (No. 2), characterized by seldom but strongest earthquakes and the Inner Dinaric Alps (No. 3) characterized by reverse faults (Fig. 2).

Until recently, the most complete study of the tectonic structure in BIH was done by Papeš (1988), who has identified deep faults passing through BIH as well as 30 tectonic units. Three significant epicentral regions can be detected in Bosnia and Herzegovina (Northern Bosnia-Banja Luka; Central Bosnia-Sarajevo, Outer Region-Herzegovina). The focal depth of 64% of all earthquakes is only 10 km; focal depth of 29.7% earthquakes is in the range from 11 to 20 km; around 4.5% the depth is at 21 to 30 km, and only 1.7% of all the earthquakes have the focal depth greater than 30 km. Shallow focal depth is another parameter influencing the destructive strength of these earthquakes. Northern Bosnia-Banja Luka occupies the territory of the central part of the Dinaric Alps, the southern part of the Pannonian Basin. The primary faults related to the southern part of the Pannonian Basin strike NE-SW. The faults striking NW–SE and

Fig. 2 Geotectonic Division of Dinarides in BIH, https://www.dinarskogorje.com/planine.html

N-S occur as a consequence of the Dinarides and Alpine related movements. The outer region-Herzegovina (south-east part of BIH) with the Dinaric Mountains is seismically deeply affected by the subduction of the Adriatic microplate under the Dinaric massif (Prelogović et al. 1982). Both, the Adriatic coast and the Dinarides are characterized by reverse faults.

Throughout history, the seismic hazard was manifested in various scales and degrees of intensity, different levels of damage of buildings together with the effects of natural force on the human population. Today, the European Macroseismic Scale, EMS-98 (Grünthal 1998) is used for the descriptive presentation of the natural disaster. For engineering purposes, such descriptions are not directly applicable. The European Standard for Construction of Earthquake Resistant Structures (Eurocode 8) for determining the forces acting on the building requires the definition of a peak ground acceleration (PGA). The probability of damage exceedance is expressed in relation to the PGA or the spectral response parameters converted from the observed macroseismic intensity. Maps of comparative PGA are made on the basis of a probabilistic analysis of the earthquake hazard.

Two maps (Figs. 3 and 4) illustrate the hazard for BIH, in terms of PGA during an earthquake, with the exceedance in 95 years and 475 years as defined in Eurocode 8. The production of the maps was done with the help of the UNMZ-Czech Office for Standard, Methodology and Testing and local experts from Bosnia and Herzegovina in 2018 and it became a part of the National Annex in BAS EN 1998-1: 2018.
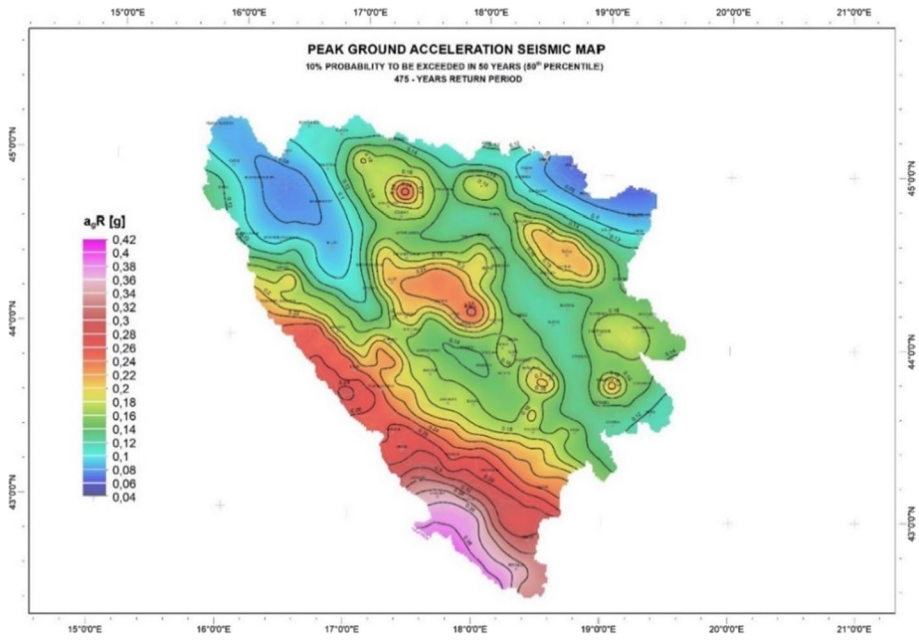
Fig. 3 Seismic hazard map for Bosnia and Herzegovina (475 years) in the function of PGA (BAS 2018)
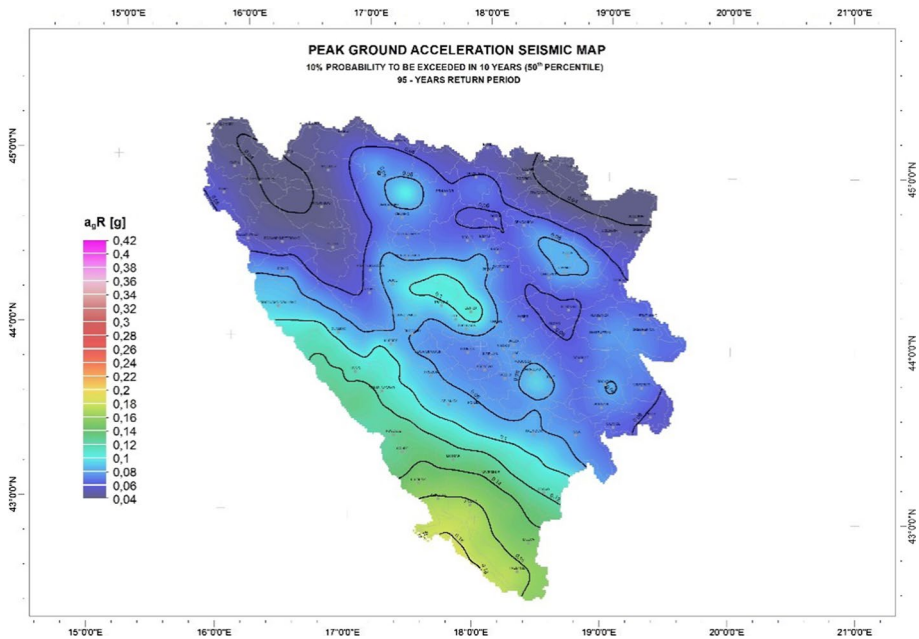

**Fig. 4** Seismic hazard map for Bosnia and Herzegovina (95 years) in the function of PGA (BAS 2018)

Fig. 5 Geographic view of Sarajevo with selected buildings

The OpenQuake engine, the open-source software for seismic risk and hazard assessment developed within the global earthquake model (GEM) initiative was used (Pagani et al. 2014). During the calculation it was decided to take into account the velocity of the seismic wave propagations of $v_{s,30} = 800$ m/s, which can be connected to soil type A (rock or other rock-like geological formation, including at most 5 meters of weaker material at the surface). It is interesting to point out that the southern Herzegovina (Čitluk, Čapljina, Ljubuški, Neum, Ravno, Stolac, Ljubinje, and Trebinje) is characterized with the highest PGA, being above 0.30 g. However, this region is not so densely populated, only 5.1% of the total population of Bosnia and Herzegovina occupy this area. The main percentage of the territory of Bosnia and Herzegovina (63.9%) may experience earthquakes of 0.1 g to 0.19 g where 58.8% of residents live (Fig. 4).

2 Study area

Sarajevo (Fig. 5) and Banja Luka (Fig. 6) were chosen for the evaluation for two reasons. Sarajevo is the largest city in Bosnia and Herzegovina with a population of 275,524 (according to the 2013 census). The city is nested in the Sarajevo valley of Bosnia, surrounded by the Dinaric Alps situated along the Miljacka River in the heart of Southeastern Europe and the Balkans. As per Papeš (Papeš 1988), the Sarajevo Fault, the longest fault, may experience earthquake series of magnitude 6 by Richter's scale or even higher. It was in 1962 when the strongest earthquake of magnitude 6.0 by Richter struck Sarajevo at the location of the biggest fault line running across the City of Sarajevo. This earthquake happened in Treskavica, a mountain near Sarajevo, and luckily there were no casualties. This can be connected to the location of occurrence and the fact that at that time Treskavica had a very low population.

Banja Luka is the second largest city in Bosnia and Herzegovina and according to the 2013 census, Banja Luka has 199,191 inhabitants. Banja Luka covers some 96.2 km² of
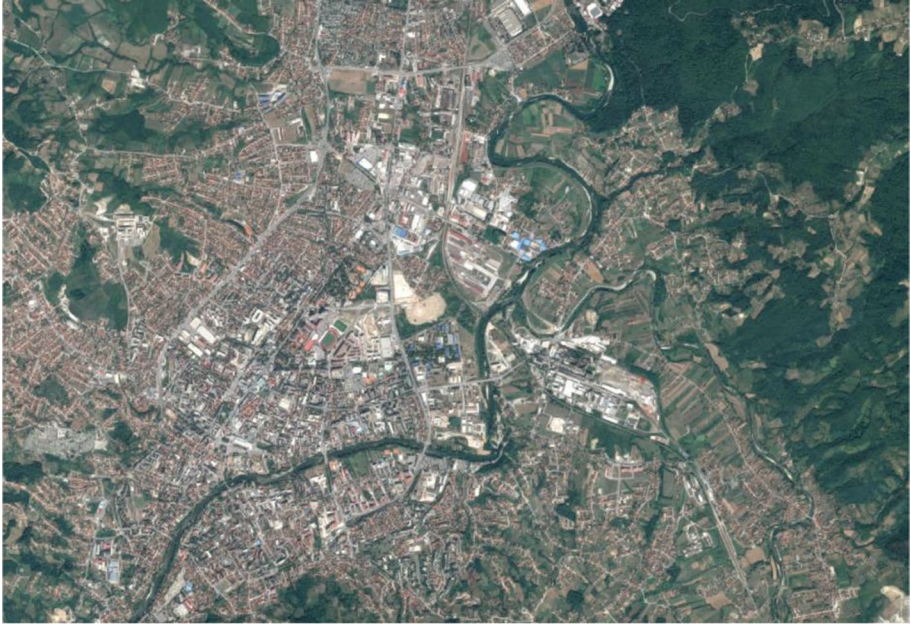
Fig. 6 Geographic view of Banja Luka with selected buildings

Fig. 7 Banja Luka after the 1969 earthquake (https://myspace.com/banjaluka4ever/mixes/classic-stare-fotog rafije-old-photographies-banja-luka-506905, accessed August 23, 2018)

land in BIH, on the Vrbas River. Banja Luka fault, the second largest, experienced a series of devastating earthquakes. Until now there have been four series of earthquakes (1888, 1935, 1969 and 1981) (Trukulja 1999).

Banja Luka was affected by the most devastating earthquake in 1969 having a 6.4 magnitude, while the intensity ranged from VII to IX by the MCS greatly depending on the soil characteristics (Stojanković 1999). The wider region around Banja Luka is characterized by low-to-moderate seismicity and intraplate in nature (Lee et al. 2015). One of the specifics of the entire region of Bosnia and Herzegovina is the low focal depth of earthquakes. In the case of Banja Luka (Fig. 7) the focal depth of the mainshock was only 25 km (shallow

earthquake). Casualties after this devastating event were noted in 15 fatalities, 1117 injured people and over $300 million in the economic loss (Trukulja 1999). The residential facilities were completely destroyed (86,000 apartments), schools were heavily damaged (266), cultural (146), health (133), and social facilities and public administration (152).

The study of past earthquakes and the investigation of the actual damage on exposed elements enables the compilation of detailed statistics on the state of damage of various types of buildings under seismic activity. Several medium-sized earthquakes affected the area of BIH in the last 50 years. Taking into account that BIH falls in the moderate seismic hazard it is justifiable to perform a seismic risk assessment and determine the probable level of damage. This is especially emphasized for the historic masonry buildings located in Banja Luka and Sarajevo. The first standards addressing the seismic requirements in the former Yugoslavia originate from 1948 (Salic et al. 2012). Load-bearing masonry construction was the most widely used form of construction for dwellings and buildings all until the end of the 1900s. The PTP2 (1948) did not limit the height of the masonry construction, which was revised in the PTP-GuSP64 (1964) limiting the height of the buildings in relation to the intensity zones and the type of constructive system (URM with rigid floors and confined masonry with horizontal and vertical cerclages). The PTP2 allowed the use of both, heavy (reinforced concrete-RC) and light (wooden) floor structures. In the period of its enforcement, the wooden floors were dominantly used for individual housing and seldom for residential buildings. After the 1963 Skopje earthquake, wooden floor structures were abandoned.

On the other hand, since 1948 the RC cast in situ or semi prefabricated rib floor systems were dominantly implemented in collective (ground floor + 4 stories) residential buildings. Confined masonry with horizontal and vertical cerclages with rigid diaphragms was introduced after the 1963 Skopje earthquake. According to the Census data (CBS 2013) for Bosnia and Herzegovina buildings made of brick, stone and concrete make up 54.10% and 53.82% of all buildings in Sarajevo Canton and City of Banja Luka respectably. In this respect, the knowledge about the seismic vulnerability of these structures is of paramount importance for the establishment of the priorities in a long-term prevention policy.

3 Database of buildings

As mentioned previously, there have been no building typology databases developed in Bosnia and Herzegovina until today. This was one of the conclusions of the project NERA (2011), which clearly indicated the lack of such a database, in which besides BIH, five European countries were identified by Cambridge Architectural Research Ltd. (CAR). The importance of such a database is in its applicability to the seismic risk assessment of buildings.

For the purpose of this paper, the macroseismic method was performed on the database formed during the research on the "Typology of Residential Buildings in Bosnia and Herzegovina" (Arnautovic-Aksic et al. 2016). This research was conducted from 2014 to 2016, within the methodological framework of the European research project TABULA[1] (IWU 2017). The main concept of the TABULA project, which was first implemented

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[1] TABULA project was harmonized with the directives 2002/91/EC and 2006/32/EC and co-financed by the European Commission's IEE program.

in 20 European countries, was to create a common system of classification of residential buildings according to their construction period, their typical architectural features and thermo-technical characteristics. The first-of-a-kind research on the typology of residential buildings in Bosnia and Herzegovina was conducted by a team of experts in architectural and mechanical engineering from BIH in collaboration with GIZ[2] and consisted of a comprehensive survey of 13,044 existing residential buildings in BIH, as well as several statistical analysis, which facilitated the selection of 29 representative buildings (namely "typical buildings") for each of the residential typological categories (Zagora et al. 2017).

The data provided by this database included the location of the building, year of construction (indirect indication of the structural system), purpose of the building, areas of the layout, number of floors, type of structural system (basically a combination of the construction materials, the load-bearing elements, and the non-load-bearing elements), type of roof, etc. The data was collected by using two questionnaires: questionnaire A and questionnaire B. The type of questionnaire A is shown in the following Table 1.

Questionnaire A was used in the first stage of the survey and it comprised of general inquires which were recorded by observation method, while the second phase consisted of individual interviews with the representatives of the households (using a more elaborate survey form-the "Questionnaire B") in order to obtain more precise information on the building physics, envelope, and heating system, etc. In the subsequent stage following the selection and detailed measurement and recordings of the 29 representative or the so-called "typical buildings" (Fig. 8), as the real representatives amongst the entire statistical sample (Zagora et al. 2017). As the research conducted for the TABULA project comprehended common attributes to the ones defined in GEM, it allowed us to use the raw data obtained for a different purpose and organized them to render the common set of attributes. Applicability of the GEM database in the seismic assessment of buildings has been proven as quite adequate in several countries. Subsequently, from the entire database in the buildings in Sarajevo and Banja Luka were extracted and in total 2933 buildings were elaborated.

This is just a first step in the data collection of buildings in Bosnia and Herzegovina, leading towards establishing an official institutionalized registry of the building typology at the national level. Knowledge regarding the construction period of a certain group of buildings and the basic characteristics of the construction method is important for a rough estimate of the earthquake resistance of buildings and the expected effects of the earthquake because the construction period can be related to the application of appropriate regulations and the level of the prescribed seismic force.

The buildings are classified into groups, according to the construction type (level of earthquake-resistant design) M5 U Masonry (old bricks) and M6 U Masonry—RC floor according to EMS-1998 (Grünthal 1998). The influence of different types of floors on the response on earthquake action was investigated (wooden slabs denoted as M_w, and reinforced concrete slabs as M_rc). Different heights of the buildings were taken into consideration as well. Up to 2 floors, a low-rise building was defined; 3-5 floors defined the mid-rise building and from 6 floors the structure was identified as high-rise. During the construction period from 1918 to 2014 it can be seen that the largest amount of structures are buildings with two stories (39.79%), one storey (25.26%), and three storeys (24.48%), while all the others are in the percentage of total 10.47% (Fig. 9).

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[2] GIZ, abbrev. German Agency for International Cooperation (*Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH*, germ.).

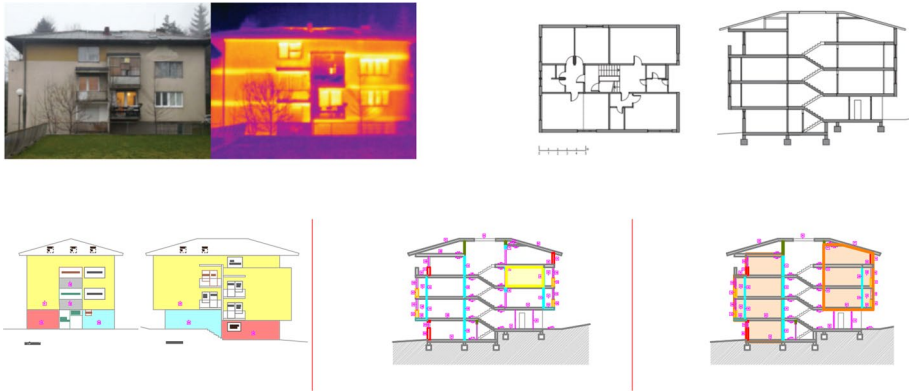**Table 1** Typology of residential buildings in bosnia and herzegovina: questionnaire A

A	Building data
A1	Address	Entity:_____ Canton:_____ Town:_____ Municipality:_____ Street name:_____ Street number (s): ☐☐☐☐☐☐☐☐☐☐
A2	Building type	1. Single-family (individual) housing: contains max. 3 dwellings 2. Multifamily (collective) housing: contains more than or equal to four (≥4) dwellings
A3a	Single-family housing sub-type, according to its urban setting	1. Freestanding single-family house (detached building located on an autonomous lot) 2. Terraced houses (attached to adjacent buildings; row houses)
A3b	Multifamily housing sub-type, according to its urban setting	1. Detached (freestanding) residential building: detached building located on an autonomous lot; max. two street numbers/entries 2. Attached residential building within an urban block 3. Apartment blocks: large scale residential buildings with more than or equal to three (≥3) entries/street numbers 4. High rise building: with more than or equal to eight (≥8) stories; detached and located on an autonomous lot; 1–2 entries
A4	Building age (construction period)	1. 1992–2014 2. 1981–1991 3. 1971–1980 4. 1961–1970 5. 1946–1960 6. 1919–1945 7. Before 1918
A5	Building floor plan shape	1. Compact building: simple floor plan shape—square, rectangle 2. Longitudinal building: simple floor plan shape, elongated rectangle 3. Complex building form: complex/jagged floor plan shape
A6	Number of stories (floors): *Ground floor and loft are considered as stories (floors)*	Basement + ground floor +____ + loft Total number of floors:____
A7	Number of dwelling units	____(total number of dwelling units)

Table 1 (continued)

| A	Building data	
A8	Ground floor surface (building base area)	1. Building length: _____ m 2. Building width: _____ m 3. Total ground floor surface: _____ m^2
A9	Roof shape	1. Pitched roof 2. Flat roof 3. Other _____
A10	Building façade age and features	1. Original façade 2. Refurbished façade 3. No façade
A111	Ground floor use	1. Dwelling 2. Public use/common area (less than half of the total ground floor area) 3. Public use/common area (more than half of the total ground floor area) 4. Public use/common area (total ground floor area) 5. _____ other (garage, storage)
A12	Quantity and typology of window openings	1. Building façade with fewer solitary windows 2. Building façade with more solitary windows 3. Building façade with large glazed surfaces
A13	Age and condition of the existing windows	1. Number of old windows _____ 2. Number of new windows _____ 3. Total number of windows: _____
A14	PHOTOGRAPHS OF THE BUILDING	

Fig. 8 Graphical study of the typical building representing the category of multifamily houses from 1961-1970
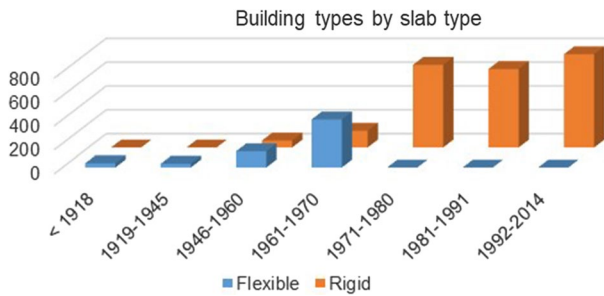

Fig. 9 Building types by number of floors
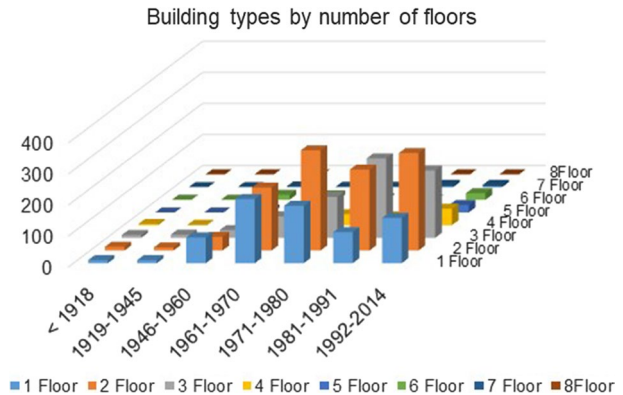
Fig. 10 Building types by the structural system
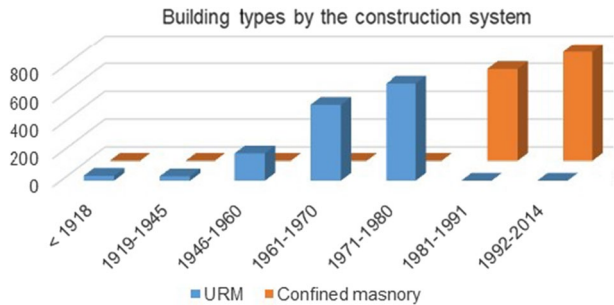
A clear distinction in the construction methodology is seen from Fig. 10, where until 1980 there is a slow progressive increase in the construction of URM buildings and after that this kind of construction is abandoned and replaced by the confined masonry. Of all investigated structures 50.90% were URM, while 49.10% were confined masonry buildings.

Fig. 11 Building types by slab type

Figure 11 indicated the change in the type of floor structure. The period from 1961 to 1970 can be identified as the cumbersome of flexible and rigid floors in the buildings located in Sarajevo and Banja Luka that were under investigation in this study. This indicates that the regulations from 1964 (PTP-GuSP64), which abandoned the usage of wooden floor structures, might not have been completely respected, implying the importance of conducting an onsite survey of the building stock in BIH. Of all investigated structures 20.53% had flexible floors, while 79.47% were with rigid floor structures.

4 Alternative vulnerability methods for masonry structures

Assessment of the vulnerability of an existing structure is subject to varying degrees of uncertainty due to differences in knowledge of old buildings in relation to buildings designed in accordance with modern standards and regulations. Each building reflects the state of knowledge at the time of its construction, contains possible concealed errors by the designer and the contractor, and it could have been exposed by earthquakes in the past or other extraordinary actions of unknown consequence. The assessment of the vulnerability of existing structures in a future earthquake is rather difficult and carries a lot of uncertainties similar to the design of a building exposed to the effects of not well-known forces, built with materials of insufficient knowledge, with unknown quality of contractors that perform the works, and interventions carried out in the past which are unknown. This is a challenging task for civil engineers. The assessment of the vulnerability should be carried out for each building in a comprehensive manner, one parameter should take into account all the unknowns associated with the structural system, the built-in materials, its degradation over time, previous use of the building, etc.

Three main components are needed for assessment of earthquake losses: an exposure model defining the spatial distribution and value of the assets, a set of vulnerability functions creating the probability of loss ratio conditional on a set of intensity measure levels, and a probabilistic seismic hazard analysis (PSHA) model, characterizing the probability of ground shaking in the region of interest.

In order to conduct an assessment of damages or losses for a group of buildings, it is necessary to have a batch of fragility and vulnerability functions, respectively. By fragility functions, one obtains the probability of exceeding the number of damage states conditional on a lot of ground shaking levels, while the vulnerability functions denote the probability of loss ratio for a number of ground shaking levels (Motamed et al. 2019). By using

damage-to-loss models, it is possible to convert the fragility functions into vulnerability functions.

A vast expansion and development of different methods for assessing and measuring vulnerability, ranging from empirical to basic and analytical as more advanced have started at the end of the '90 s. Methods differ in the required data, or the lack of such, for their application, level of complexity, calculation time and required assumptions. All of these methods carry some uncertainties and it is a great challenge for the researches to overcome them as this will have a direct impact on the results of the vulnerability and consequently in the process of estimation and prediction of earthquake risk.

4.1 The macroseismic method

The macroseismic method, originally developed by authors Giovinazzi and Lagomarsino (2004) under the framework of the European project RISK-UE (RISK-UE 2004), implying the probability theory and fuzzy-set theory on the vulnerability classes provided in EMS-98 (Grünthal 1998) has found its wide application in the assessment of numerous building typologies. Vicente (Vicente et al. 2011) proposed a methodology implemented for the vulnerability assessment, damage and loss scenarios for the city Centre of Coimbra, Portugal, using a GIS mapping application. Athmani et al. (2015) investigated the application of the methods for the seismic vulnerability analysis of historic masonry buildings, mainly constructed of rubble stone and adobe. The data used in the research conducted by Athmani et al. (2015) was not originally developed for seismic purposes, but extracted from the general program of a building-by-building detailed survey in which buildings were arranged according to their degradation state, with the aim of defining retrofitting and maintenance priorities. This proved that even data not dedicated to seismic assessment could be used in the macroseismic method representing a first step in the vulnerability assessment of existing buildings. Mansour et al. (2013) through the analysis indicated the existence of a high level of vulnerability in the city of Tunis leading to the necessity of mitigation measures. It was concluded that this method is suitable for cities having no complete data on building stock and without post-seismic observations. The application of this method for RC buildings was done by Guéguen et al. (Guéguen et al. 2007) for the moderate-to-low seismicity of the Grenoble city in France. Martínez-Cuevas and Gaspar-Escribano (2016) after the 2011 Lorca earthquake reassessed the intensity estimates from the vulnerability and damage distributions. It was concluded that the direct application of vulnerability modifiers is not able to reproduce in a correct manner the observed damage patterns, this being especially true for the soft storey mechanics. They have concluded that further research is necessary for vulnerability modifiers, as a simple addition of several modifiers could be inappropriate, and non-linear interactions or multiplicative effects between the different modifiers are to be considered. Additionally, it was proposed to include the non-structural components in the vulnerability analysis. Hadzima-Nyarko et al. (2016) conducted an analysis of the confined masonry in the city of Osijek using data requirements as set in the GEM building typology.

Aguilar-Meléndez et al. (2018) proposed a probabilistic version of the VIM, which is called the vulnerability index method-probabilistic (VIM_P). In order to conduct this analysis, vital data regarding seismic hazard and vulnerability of the building stock is needed. Seismic hazard is defined in accordance with the EMS, by means of the exceedance rates of macroseismic intensities. Seismic vulnerability is determined by the application of the vulnerability probability density functions (pdf) which describes the probability distribution

of the corresponding vulnerability index. PDFs employ the usage of beta-like functions. Depending on qualitative and quantitative availability of data the VIM_P defines seismic vulnerability by means of three vulnerability curves, Lower, Best and Upper.

Although several modifications for seismic risk assessment have been proposed, they all are based on the well-known vulnerability index method (VIM). The vulnerability is measured through the vulnerability index V and the ductility index Q (which is taken to be equal to 2.3), both being dependent on the building typology and its construction features.

Seismic effects (hazard) are defined by the macroseismic intensity, taking into account the five damage (ranging from 0-no damage to 5-destruction) grades defined in EMS-98 on rigid soil conditions. Different soil characteristics can be taken into account through the vulnerability index.

The vulnerability index for a set of buildings, taking into account, all possible refinements is obtained from the Eq. (1)

$$V_I = V_I^* + \sum_k q_k \Delta V_m + \sum_k r_k \Delta V_r + \sum_{j=1}^{3} \sum_{S=B}^{E} m_j \Delta V_{S_{M,j}} + \sum_{j=1}^{3} \sum_{S=B}^{E} rc_j \Delta V_{S_{RC,j}} \qquad (1)$$

which takes into account the effective ratio of the buildings affected by each modifier (Giovinazzi and Lagomarsino 2003). Where V_I^* is the vulnerability index in the function of the typology of the building, ΔV_m the seismic behavior modifier attributed through expert judgment, ΔV_r represents a regional modifier, while the change in the soil characteristics is covered by the soil amplification modifier ΔV_s. If some kind of behavior or regional modifiers have been recognized for some buildings, this ratio is covered by q_k and r_k. In order to take into account, the specific class of height j, built on soil class S, m_j and rc_j modifiers were introduced for masonry and reinforced concrete buildings respectably.

In order to take into account, different soil effects Giovinazzi and Lagomarsino (2003) made reference to EC8 (EN 1998-1:2004). The multiplication factor is obtained for different structural types (masonry and RC structures) and different heights (low, medium, high), as a function of different soil conditions with respect to the same effect if it was built on Rock (Ground Type A). In that respect, the multiplying factors are defined as

$$f_{PGA} = \frac{S_a[T_1]_{Soilk}}{S_a[T_1]_{SoilA}} \qquad (2)$$

Once a correlation between the macroseismic intensity $I_{EMS}-98$ and the PGA is formulated

$$PGA(a_g) = c_1 c_2^{(I-5)} \qquad (3)$$

where c_1 is the peak ground acceleration value a_g matching to the reference intensity I and c_2 takes into account the rate of the PGA increase with intensity I.

Taking into account the $I - a_g$ correlation, the multiplying factor (Eq. 2), is translated into the intensity increments as:

$$\Delta I = \frac{\ln f_{PGA}}{\ln c_2} \qquad (4)$$

Once this is done it is possible to represent the soil amplification modifiers ΔV_s as a function of the intensity increment, as:

$$\Delta V_s = \frac{\Delta I}{6.25} \tag{5}$$

This is applicable when the correlation between intensity and vulnerability is given by an analytical expression, resulting in vulnerability curves (Giovinazzi and Lagomarsino 2004), defined as:

$$\mu_D = 2.5\left[1 + \tanh\left(\frac{I + 6.25V_I - 13.1}{Q}\right)\right] \tag{6}$$

where I is the seismic hazard in terms of a macroseismic intensity. In this way, the hazard is correlated with the mean damage grade μ_D of the binormal distribution in terms of vulnerability rate.

Direct reciprocity between intensity and vulnerability is clearly indicated in Eq. 6, giving its input for Eq. 5.

Equation 6 is an indicator of the mean damage value μ_D in the range from 0 to 5 of the expected discrete damage distribution, in accordance with the five damage grades defined in EMS-98.

$$\mu_D = \sum_{k=0}^{5} p_k \times D_k \tag{7}$$

where p_k is the probability associated with a specific damage grade D_k, in the range from 0 to 5.

The ductility factor Q which defines the slope of the vulnerability function was taken to be equal to 2.3 for masonry structures as given in (Giovinazzi 2005) after calibration and validation and further applied in (Athmani et al. 2015).

For the probabilistic assessment of damage distribution and vulnerability curves, the binomial distribution is assumed. In that sense, the probability p_k of each damage grade, for a certain mean value of damage grade μ_D is evaluated by the probability mass function defined as in Eq. 8

$$\text{PMK}: \ p_k = \frac{5!}{k!(5-k)!}\left(\frac{\mu_D}{5}\right)^k\left(1 - \frac{\mu_D}{5}\right)^{5-k} \tag{8}$$

where ! is the factorial operator.

4.2 Typology vulnerability index

In order to determine the typology vulnerability index, several steps have to be followed. Defining the building typology is the starting point. Once this is determined then average vulnerability indices can be assigned to the vulnerability classes (Milutinovic and Trenda-filoski 2003). Milutinovic and Trendafiloski (2003) within the Project RISK-UE defined 23 building classes according to the construction material. In that respect ten classes were defined for masonry (M), seven for reinforced concrete (RC), five for steel (S) and one for wooden (W) buildings.

The upper and lower bounds of the possible values of the final vulnerability index value, for the specific building type, are represented by V_{Imin} and V_{Imax}. The most plausible value for the specific building type V_I^* (the typological vulnerability index) is calculated as the

Typology	Description	Vulnerability indices				
		V_{Imin}	V_I^-	V_I^*	V_I^+	V_{Imax}
Masonry						
M3.1	URM wooden slabs	0.46	0.65	0.74	0.83	1.02
M3.4	RC slab URM	0.30	0.49	0.616	0.793	0.86
M4	Reinforced or confined masonry walls	0.14	0.33	0.451	0.633	0.70

Table 2 Vulnerability index valued for masonry wall (Milutinovic and Trendafiloski 2003)

Data origin	ΔV_f
Non-specified existing database	0.08
Data specifically surveyed for vulnerability purposes	0.04

Table 3 Suggested values of ΔV_f (Giovinazzi and Lagomarsino 2004)

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^*.

Since the buildings in the database can be divided into three types: unreinforced masonry with wooden (flexible) slabs, unreinforced masonry with a reinforced concrete slab (rigid diaphragm) and confined masonry, the vulnerability index values for masonry structures with different floors are given in Table 2 according to Milutinovic and Trendafiloski (2003). According to EMS-98 (Grünthal 1998), the most probable vulnerability class of unreinforced masonry with timber floors is B, and for unreinforced masonry with rigid diaphragms and confined structures is C.

As the database of a building inventory that has been used has had been compiled for reasons different than seismic risk assessment data it was necessary to conduct corrective measures. This is covered by the width of the filter function ΔV_f (Table 3), which is a function of the quantity and quality of available data (Giovinazzi and Lagomarsino 2004).

4.3 Regional and behavior modifiers

For the computation of the final vulnerability index V a behavior modifier factor of a building is introduced ΔV_m, by which the vulnerability index V_I^* from Table 2 can be increased or decreased. The behavior modifier of a building can be calculated according to the Eq. 9 (Giovinazzi 2005):

$$\Delta V_m = \sum_k \Delta V_{m,k} \tag{9}$$

where ΔV_m—the behavior modifier factor, $V_{m,k}$—modifying scores.

In order to categorize the behavior modifiers, the empirical formulation was utilized based on the observed typical damage patter, including the recommendations provided in several Inspection Forms (Benedetti et al. 1988) and in the prior proposal given by Spence et al. (1992). It is on the basis of expert judgment that the modifying scores are ascribed, but as well they have been, to a certain extent, calibrated by the obtained knowledge from the previous vulnerability evaluations (Giovinazzi and Lagomarsino 2004). The behavior modifiers were defined and chosen according to the expert judgment and guidance by
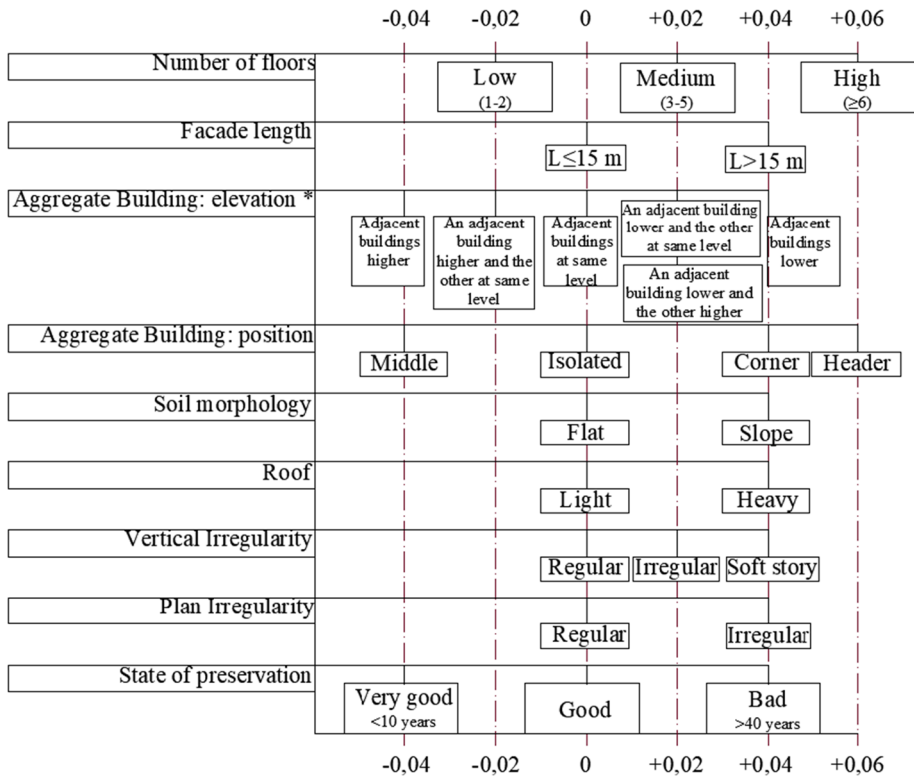
Fig. 12 Behavior modifiers according to Milutinovic and Trendafiloski (2003) and extended with Lantada et al. (2010)

the previous works conducted by Milutinovic and Trendafiloski (2003) and Lantada et al. (2010), as there is no available data of damaged buildings after earthquake action in Bosnia and Herzegovina. In order to take into consideration, the geometric irregularities, the values proposed by Milutinovic and Trendafiloski (2003) and extended with Lantada et al. (2010) were taken for the behavior modifier factors ΔV_m. A description of nine categories of the behavior modifiers and the values of the individual behavior modifiers used in this specific study is shown in Fig. 12. For a single building, the total behavior modifier is obtained as the sum of the individual values for these categories. It should be noted that the categories façade length, soil morphology and state of preservation were not taken into account in this research.

Building typology at the regional level is taken into account by the regional vulnerability factor V_r. Through this factor, various construction techniques are considered which may be specific and unique to a certain region of different European Countries indicating that the range borders are quite large. By applying the vulnerability factor V_r which is based on the available historical data or expert judgment the V_I^* typological vulnerability index will be revised. A valid expert judgment has to be a result of precise technological, structural, and constructive information arguing a better or worse average behavior with regard to the one which is proposed in Table 2 for URM and confined masonry buildings in this research. In the case of availability of the observed damage, certain modifications have

Table 4 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

to be done, with the goal of getting a better approximation, and this is done by shifting the average curve. Oliveira and Mendes Victor (1984) investigated a massive stone typology in Lisbon and they suggested a value of $V_r = 0.12$ which would offer better behavior with respect to the average value. On the other hand, in Spain after the Lorca 2011 earthquake, Feriche et al. (2008) suggested values of the regional vulnerability factor in the range from 0.08 to 0.16 depending on the structural types and years of construction which is connected to the seismic codes in force at a specific time. For the vulnerability of Georgia, Tsereti (Tsereteli et al. 2014) proposed values for the regional vulnerability factors based on the expert judgment and the actual observable inventory. The regional vulnerability factors for RC structures were zero, while for pre-code low rise and mid-rise masonry structures with RC floors the values were in the range of 0.12 and 0.15, while the highest values were given to the masonry buildings made of simple stone in the amount of 0.25. We didn't use the regional modifiers because our traditional constructive techniques for masonry buildings are relatively good.

4.4 Translation to the EMS-98 vulnerability classes

EMS-98 has introduced vulnerability classes that are useful for the distinction and classification of structures with respect to their response due to earthquake actions. In all previous scales, the relationship was made between the construction type and vulnerability. For the first time in EMS-98 seismic resistance of buildings was categorized in a broader sense taking into account not only the type of the structure but as well construction, the regularity of the structure, state of preservation, etc. This as a consequence implied the formation of a table of vulnerability values. In this sense, it is suitable to transform the obtained estimated values of V_I into the vulnerability classes as introduced in the EMS-98 (Table 4). This should be done as most of the vulnerability assessment and damage reports use the EMS-98 scale making it then more feasible and comparable. EMS-98 classification has numerous benefits: the existence of transition classes (class ranges), which considers the influence of factors on the vulnerability values and ranges, the dispersion of existing knowledge can be designated through the vulnerability values, and simplified graphical elements can be used for illustration of the probability of expectations.

Although the existence of a transition class of vulnerability is an advantage of EMS-98, assigning a specific vulnerability class to an analyzed building, which is not most likely not the vulnerability class, requires expert opinion and judgment, so the problem becomes more complex. Also, in EMS-98, when determining the most probable grade of vulnerability, it is not clearly stated whether one is to take into account the number of storeys, impact of adjacent buildings (block position), surrounding terrain, foundations, etc. All this

Table 5 Relation between V_I and EMS-98 class (Martínez-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

affects the earthquake resistance and is taken into account in the macro-seismic method. Therefore, in this paper a connection between the vulnerability coefficient and vulnerability class, and at the end, the influence of the behavior modifier (i.e. factors such as the number of storeys, location in the block, etc.) will be presented, which in some cases will alter the vulnerability class.

Each value of V_I is obtained by adding all the behavior modifiers and regional modifiers. After this one is able to calculate the average value of V_I. The values of the vulnerability indices V_I can be put in relation to the EMS-98 vulnerability class by utilizing Table 5 which were resulted from the modifications conducted by Milutinovic and Trendafiloski (2003). Martínez-Cuevas and Gaspar-Escribano (2016) showed this connection in their research (Table 5).

5 Results

5.1 Vulnerability curves

In the risk analysis of every analyzed structure, it is necessary to determine the vulnerability index, as a representation of the vulnerability module, which is defined between two limits: zero, representing a well-designed seismic-resistant building on one side, and on the other, a structure with bad seismic response will be awarded a value of one. Semi-empirical functions (Giovinazzi 2005; Lantada et al. 2009, 2010) associate vulnerability with macroseismic intensity, enabling the computation of the mean damage grade (MDG) for each considered building. The MDG and the simplified assumptions on damage distribution are utilized as input values to create damage probability matrices (DPM). A complete distribution of the damage in the building (five non-null damage states are considered) is formulated by the DPM. On the basis of the weighted mean damage index, the expected damage and risk of each building are computed taking into account the contribution to damage of all the buildings in the studied area. Average mean damage grades for URM with flexible floors, URM with rigid floors and confined masonry are presented in Fig. 13. As expected, the URM with flexible floors is to experience the heaviest damage in an earthquake event and the least damage would be experienced by confined masonry structures. The difference in the average mean damage grade of the URM with rigid floors and confined masonry in respect to the URM with flexible floors is the largest in the lower intensity IV being 44.24% and 76.75% respectably, and reducing to 38.08% and 71.85% for intensity VII respectably, while this difference in XII intensity reduces to only 3.12% and 11.74% respectably. It can be concluded that for higher intensities slab type does not have a
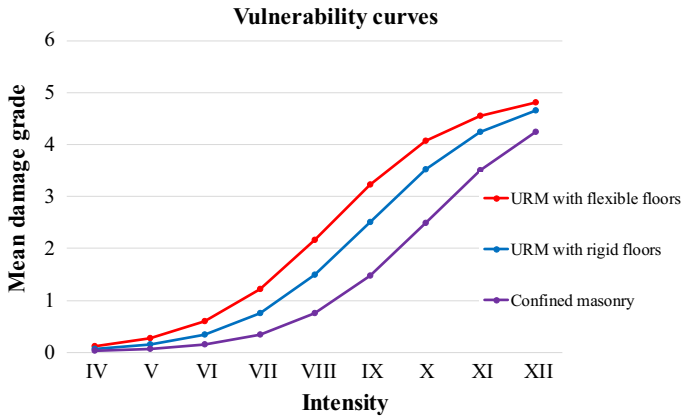
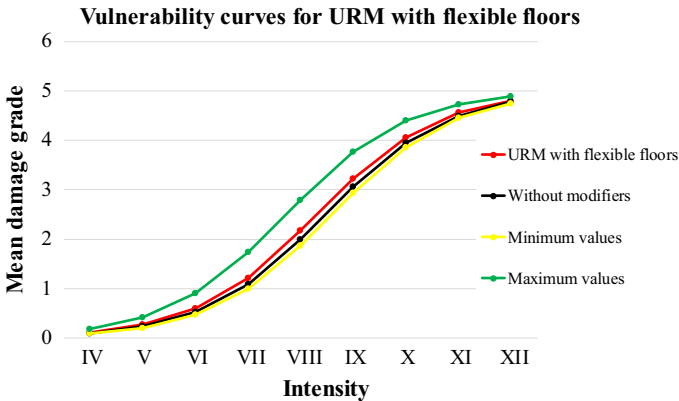**Fig. 13** Average mean damage grades for the whole database

Fig. 14 Vulnerability curves for maximum and minimum obtained mean damage grades for URM with flexible floors

major effect on the structural response, which is something that cannot be stated for lower intensities. Confined masonry in the lower intensities (IV and all up to VIII) would have a smaller damage grade of 58.30% and 49.79%, while the difference becomes very small (8.90%) at XII intensity. The average mean damage grade (AMDG) increase for all construction types from IV to V intensity is around 35%. The largest increase for all building types is noted from V to VI intensity in which for confined masonry the AMDG increase was 132.57%. A smaller increase of the AMDG for both types of floors is noted from IX to X intensity, while for confined masonry this behavior is noted in the transition from intensity XI to XII.

After calculating the average mean damage grade for every structural type, the influence of behavior modifiers is determined as well, as presented in Fig. 14 for URM with flexible floors. The influence of the modifiers can be considered significant for smaller intensities because for intensity IV it is 13.73%, while for medium and high intensities its importance is irrelevant (for intensity VIII 8.19% and for intensity XII only 0.59%).
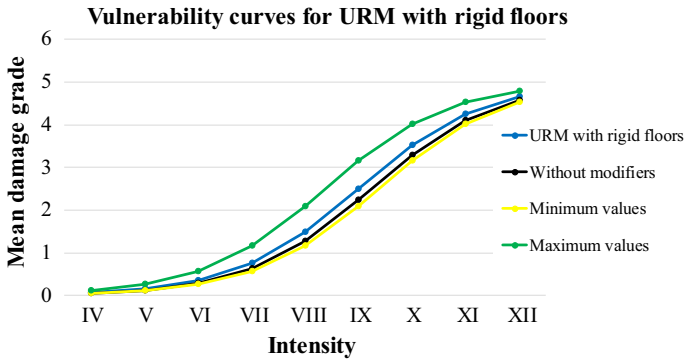
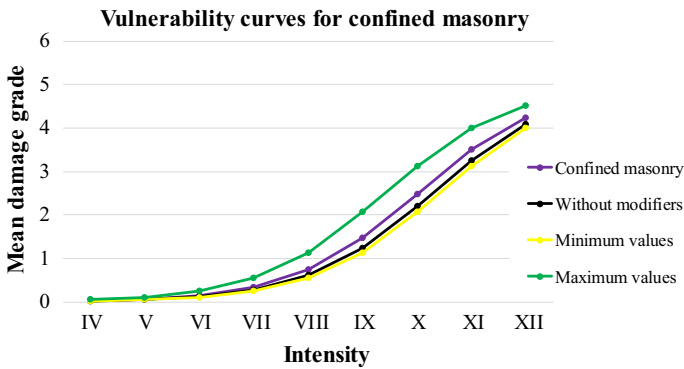**Fig. 15** Vulnerability curves for maximum and minimum obtained mean damage grades for URM with rigid floors

Fig. 16 Vulnerability curves for maximum and minimum obtained mean damage grades for confined masonry

Table 6 Average values of the vulnerability index

Building type	Typological value V_I^*	The average value of the modifiers $\sum \Delta V_m$	The average value of the vulnerability index V_I
M3.1	0.740	0.0268	0.767
M3.4	0.616	0.0406	0.657
M4	0.451	0.0430	0.494

The difference between the vulnerability curves obtained from minimum value and without using the modifiers is almost the same with the highest difference of 10.11% for intensity IV. However, if maximum values are used in the creation of the vulnerability curve the mean damage grades are increased for up to 38.5% in intensity IV, 29.94% for intensity VII, to only 1.56% for XII intensity.
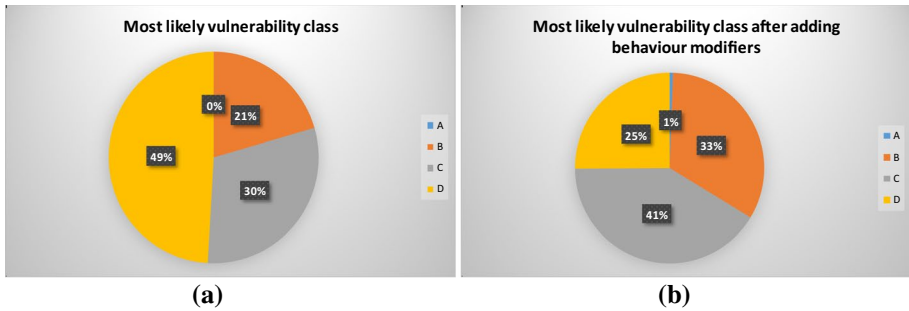
Fig. 17 Most likely vulnerability class according to EMS-98: a) for the structural type according to the vulnerability table (Grünthal 1998), b) after the influence of behavior modifiers using the macroseismic method

Identical calculations were made for URM with rigid floors and confined masonry (Figs. 15 and 16). A very similar pattern of average mean damage grade for URM with flexible and rigid floors is noted.

5.2 Vulnerability classes

Based on formulas (1), (6) and (9), and by applying the behavior modifiers based on the visual inspection of each building, the vulnerability index was calculated and the intermediate degree of vulnerability for each building. The average values of the vulnerability index and the behavior modifiers are shown in Table 6.

The effect of the behavior modifier is reflected in the change of the vulnerability index values. This also means that some vulnerability classes have also changed (for example, the building of vulnerability class B now passed to a vulnerability class A). For the observed database, the-17 buildings URM buildings with flexible floors have passed from class B to class A of vulnerability (common characteristics of these 17 buildings are: age greater than 100 years, located at the ends of the rows or on the corner, have a heavy roof structure). 368 masonry buildings with RC rigid floors went from the vulnerability class C into vulnerability class B due to modifier change: complex layouts, single standing structures with 3 or more floors, having a heavy roof structure. While 704 confined masonry buildings transferred from the vulnerability class D into vulnerability class C due to modifier change: complex layouts, single standing structures with 3 or more floors, having a heavy roof structure. The results are shown in Fig. 17. In Fig. 17a it is evident that using vulnerability table from EMS-98, most likelihood vulnerability class for URM with flexible floors is B, for URM buildings with rigid floors is C and for confined masonry is D. After adding the behavior modifiers to the typology values of vulnerability index, the situation is different (Fig. 17b). It is evident that the influence of these parameters (position of building in the block, number of floors, etc.), which is not used in EMS-98, is rather high. As can be seen, the largest impact was on the buildings belonging to vulnerability class D where there has been a half-hold change with the application of modifiers. The largest impact on this can be attributed to the type of roof structure, complex structure and the number of floors. It may be argued that the largest contributor was the number of floors. However, the influence of behavior modifiers is not as high as it was expected for URM with flexible floors. The

Table 7 Damage states for mean damage degrees (Lantada et al. 2010)

Intervals of mean damage degrees	Most likelihood level of damage of certain limit states	Damage level according to EMS-98
0–0.5	No damage	D0
0.5–1.5	Slight	D1 (state 1)
1.5–2.5	Moderate	D2 (state 2)
2.5–3.5	Significant to severe	D3 (state 3)
3.5–4.5	Very severe damage	D4 (state 4)
4.5–5.0	Total collapse	D5 (state 5)

Table 8 Average values of mean damage grades for three levels of intensity

Intensity	Average μ_D for M3.1	Average μ_D for M3.4	Average μ_D for M4
VII	1.217	0.754	0.343
VIII	2.169	1.484	0.745
IX	3.229	2.504	1.470
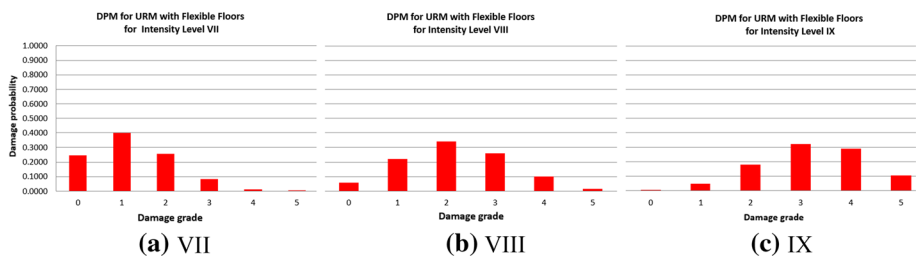
Fig. 18 Damage probability matrices for URM with flexible floors for three-level of intensity: a) VII, b) VIII and c) IX

reason is that most of the buildings are isolated or situated in a row and have only 1 or 2 storeys, which reduced the average values of the behavior modifiers.

Table 7 shows the relationship between the values of mean damage degrees μ_D with the most likely level of vulnerability according to EMS-98.

Table 8 shows the corresponding mean damage grades expected in URM and confined masonry for three levels of intensity (VII, VIII, and IX) that are quite probable for this region. It can be seen that URM masonry with flexible floors has much lower seismic resistance when the mean damage grade is related to the probable damage grade. For earthquake intensity VIII, it can be seen that moderate damage can be expected to be observed in these buildings. Also, for intensity IX, both URM structures are expected to suffer significant to severe damage, but it should be noted that masonry structures with reinforced floors could as well be classified into a lower damage degree as the value is on a limit between the two levels. On the other hand, confined masonry structures in earthquakes intensities VIII and IX are expected to experience slight damage.

Using a mean degree of damage, with the help of the binomial distribution, damage probability matrices are obtained. Figures 18, 19 and 20 show DPM for all three types
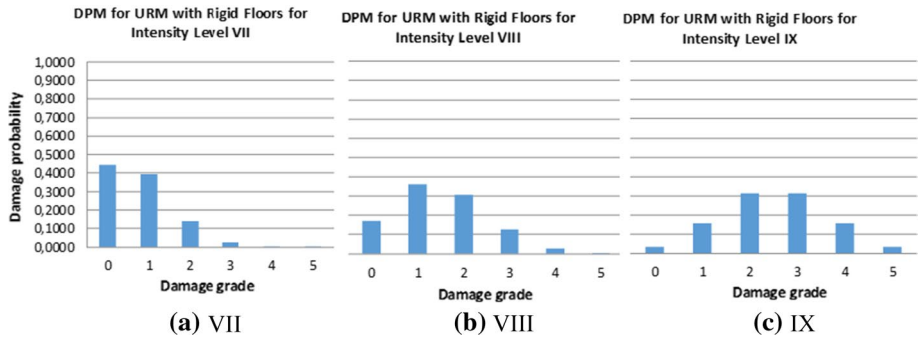
Fig. 19 Damage probability matrices for URM with rigid floors for three-level of intensity: a) VII, b) VIII and c) IX
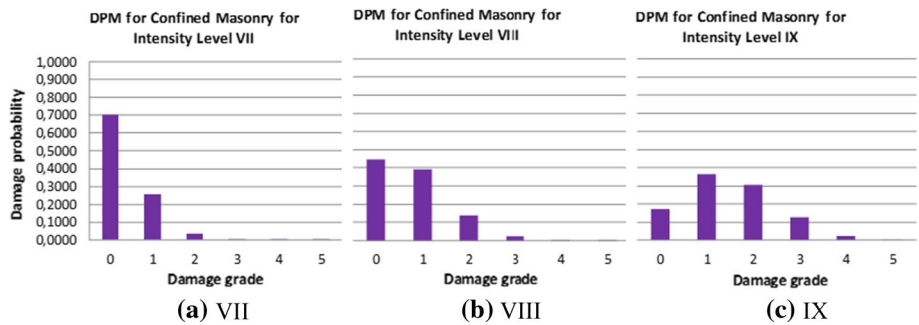

Fig. 20 Damage probability matrices for confined masonry for three-level of intensity: a) VII, b) VIII and c) IX

of construction for three levels of earthquake intensity that can be expected in this region. It is interesting to note that in the case of VII earthquake intensity no damage would be experienced by a large majority (70.13%) of confined masonry structures, which is not the case for URM structures with rigid floors (44.19%), and URM structures with flexible floors where only 24.80% would remain undamaged. Almost the same percentage of URM structures regardless of the slab type would experience damage grade 2 if exposed to intensity level VIII (36.16% RC floor and 30.63% flexible floor), while only 13.69% of confined buildings would experience this damage grade indicating its better response to seismic actions.

The methods that have been applied here are suitable for regions where there is no available data regarding buildings and no seismic damage data, as is the case of Bosnia and Herzegovina. In can be concluded that the probable seismic performance of designated buildings can be formulated on the basis of results obtained from the simplified vulnerability assessment procedure. This can be identified as a starting point for shortlisting potential buildings that would require a more thorough vulnerability assessment. With such data in hand, the preparation of emergency plans for earthquake risk mitigation could be envisaged.

Table 9 Seismic events of reference

References	Earthquake	Intensity scale	Damage grade	Label
Galizia and Fiorenza (2016)	Banja Luka, 27.10.1969	MSK-64	5	Banja Luka'69
	Bucharest 04.03.1977	EMS-98	5	Bucharest'77
	Irpinia 23.11.1980	MSK-76	5	Irpinia'80
	Lisbon – various earthquakes	MM	5	Lisbon
	Mont Chenoua 29.10.1989	VIII MM	5	Mont Chenoua
Bernardini et al. (2010)	Irpinia 23.11.1980	EMS-98	5	Bernardini et al. (2010)

References	Method	Vulnerability class	Label
Ferreira et al. (2014)	Vulnerability index method	A	Ferreira et al. (2014)
Salazar and Ferreira (2020)	Vulnerability index method	A	Salazar and Ferreira (2020)

5.3 Comparison of the results

The evaluation of the obtained vulnerability curves was done by the comparison of the data of damage of various structural typologies and vulnerability classes in several countries that were presented in the studies of Bernardini et al. (2010), Ferreira et al. (2014), Galizia and Fiorenza (2016), and Salazar and Ferreira (2020). The conventional definitions of damage degrees and vulnerability classes of the building types have been assumed according to the EMS98 macroseismic scale.

In the study of Galizia and Fiorenza (2016), the authors provided the reference, the damage grade, the macroseismic intensity, and a label containing the place and the date for every seismic event. The data applicable in this study are presented in Table 9. As stated in Galizia and Fiorenza (2016), the problem of the heterogeneity of the data was overcome by using the expressions and considerations based on the correlations between the different macroseismic scales and the damage levels (ATC-13 1985; Achard and Goula 1988; Abeki et al. 1989; Bolt 1999; Okada and Takai 2000).

Data regarding the observed damage, compiled in damage probability matrices (DPMs), have been used in Italy to analyze vulnerabilities and forecast the expected damage, particularly after the 1980 Irpinia earthquake (Braga et al. 1982). Based on the available data, seismic damage scenarios and risk analyses for residential buildings, using the definitions of damage degrees and the implicit Damage Probability Matrices (DPMs) suggested, if only qualitatively, by the EMS98 macroseismic scale was done in the paper of Bernardini et al. (2010) (Table 9). Empirical vulnerability curves that summarize statistics on observed damage levels produced by the Irpinia earthquake (Braga et al. 1982), up to the local intensity X was presented in Bernardini et al. (2010).

The validation was also made with the existing vulnerability curves obtained using different seismic vulnerability methods. The data for this kind of comparison are presented in Table 9.

Ferreira et al. (2014) used the vulnerability index method for façade walls of traditional masonry buildings and presented its subsequent application to over 600 building façades from the old building stock of the historic city center of Coimbra. They
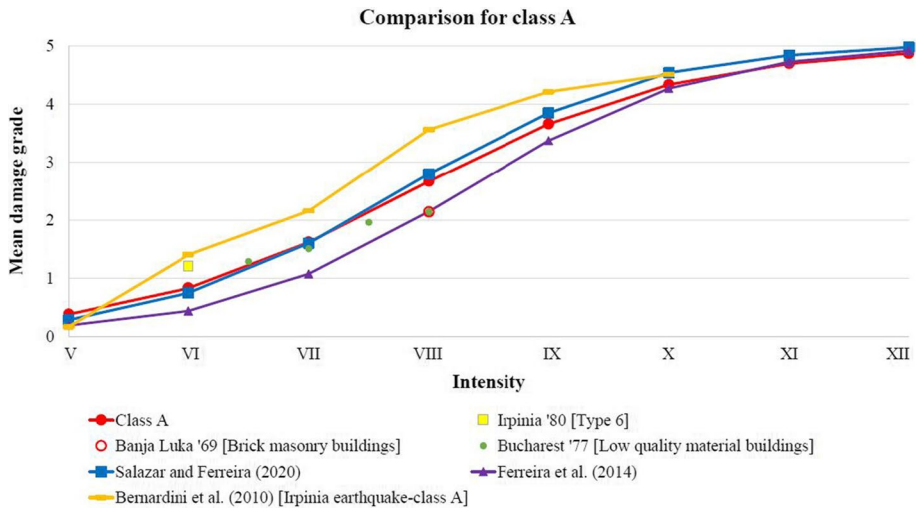
Fig. 21 Comparison of vulnerability curves for buildings class A

also presented the curve provided for buildings, and in this study, the comparison of the results was made with this vulnerability curve.

Salazar and Ferreira (2020) used the vulnerability index method, based on the assessment of 14 parameters within the vulnerability index, organized into four groups. The seismic vulnerability assessment was performed for the Historic Downtown of Mexico City (La Merced Neighborhood), thus showing the analysis of 166 historic buildings. Almost 75% of the assessed buildings are assigned the vulnerability class A in the European Macroseismic Scale (EMS-98) and for those buildings, the vulnerability curves were presented.

Figure 21 presents vulnerability curves in terms of the distribution of the mean damage values μ_D (i.e. obtained vulnerability curves in this study presented in red in all figures) for the unreinforced masonry buildings with flexible floors, which belong to vulnerability class A. Although in this study there is not a high portion of this vulnerability class, it is decided to present the comparison with available data as well. From this figure, it is clear that the curve obtained by Salazar and Ferreira (2020) gives almost identical results. In fact, only some slight differences are observed between the results obtained from the two approaches. For instance, for higher intensities ($I_{EMS-98} > IX$) the curve obtained in this study slightly underestimates the probable damage grade. As can be seen in Fig. 21, equally good results were achieved for the data of earthquake in Bucharest (1977). A slightly larger deviation was obtained for data from earthquake Irpinia, but it is assumed that the cause of higher mean damage grades is a slightly different typology of buildings (stone buildings). In practice, these values of mean damage grades mean that significant damage can be expected, even for a moderate intensity- a fact that underlines the need for a detailed seismic risk assessment for this area.

In Fig. 22 vulnerability curves obtained for vulnerability class B according to EMS-98 in this study are compared with the curves from Irpinia (yellow color) and data of damages from Bucharest (1977). Again, the results of the Bucharest earthquake show very good agreement with the curves in this paper. The differences with the Irpinia curves show again an underestimation of the mean damage grades.
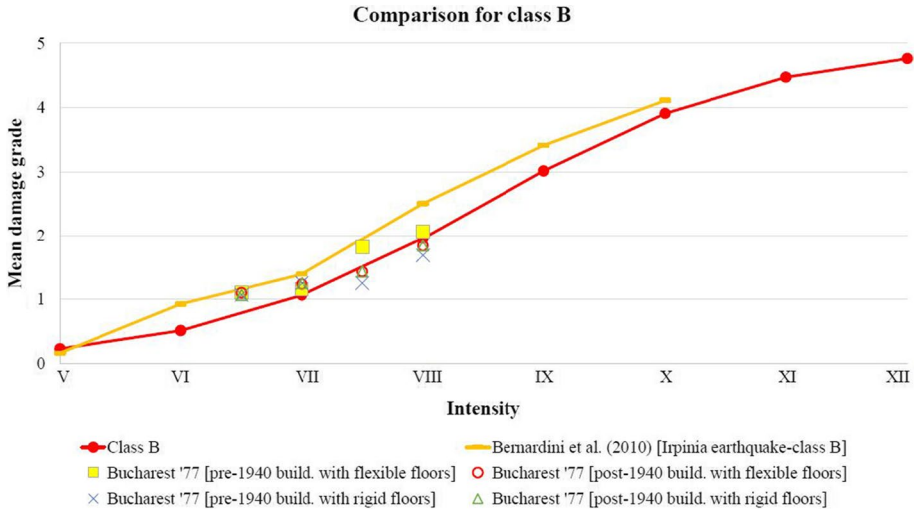
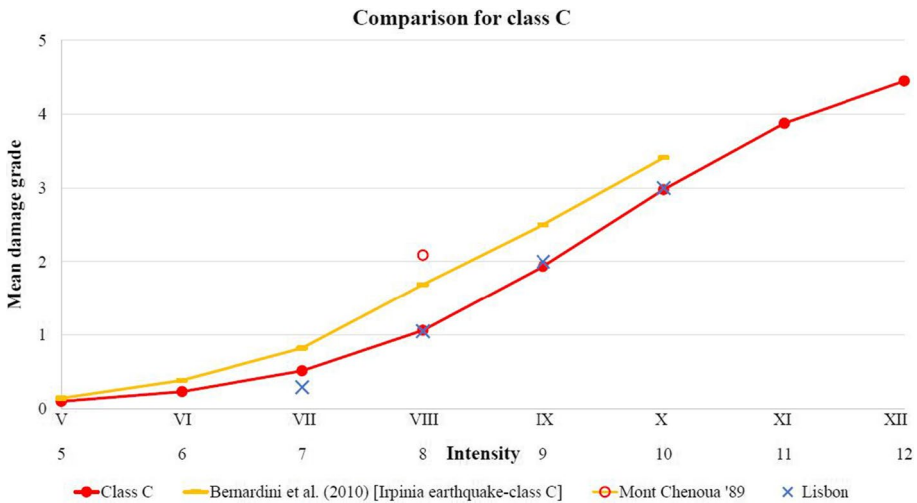**Fig. 22** Comparison of vulnerability curves for buildings class B

Fig. 23 Comparison of vulnerability curves for buildings class C

In Fig. 23 vulnerability curves obtained in this study for vulnerability class C are compared with the curves from Irpinia (yellow color) and data of damages from Lisbon. The differences with the Irpinia curves are smaller. A good agreement is achieved with the results obtained from Lisbon data.

It can be concluded that the curves obtained in this study demonstrate its reliability when compared with other data and/or curves. Issues that have been briefly mentioned in the paper, such as the one related to the site effects due to the soil typology, and some other parameters not taken into account in this paper, could influence significantly the proposed outcomes.

6 Conclusion

The main goal of this work is to reach a new, scientifically and professionally based knowledge that will serve the city authorities to decide, as responsible decision-makers, on the measures to be taken in the forthcoming short and medium-term with the aim that human casualties and economic losses are reduced to the smallest possible measure in the case of earthquake occurrence. The collected data on buildings, visual inspection, and the available documentation were placed in the database and analyzed. An empirical method of estimating earthquake damage, the macroseismic method was utilized. The vulnerability index is calculated by the macroseismic method which is in the function of the most likely value of the vulnerability index of a type of building, the regional damage factor and behavior modifiers. The effect of behavior modifiers is expressed in the increase in the vulnerability index.

Based on the calculated vulnerability index and the proposed ductility index, the average degree of damage to each building for three levels of earthquake intensity is calculated. The mean degree of damage can be correlated with the most likely level of damage according to the EMS-98. For an individual type of building, the mean degree of damage is calculated. On the basis of conducted calculations, it was determined that URM with wooden floors for VII degree of intensity would suffer slight damage (the most likely level of damage), for VIII degree of intensity moderate damage, and for IX degree of intensity is significant to severe damage. On the other hand, slight damage would be observed on URM with rigid floors for VII and VIII degree of intensity and for IX degree of intensity moderate damage may be expected. Slight damage is foreseen for confined masonry for when the intensity is in the range of VIII and IX. These calculations are also used for calculations of damage probability matrices, which allow one to evaluate direct economic losses. The behavior modifier which had the largest influence on the change of the vulnerability class was the number of floors. Buildings belonging to vulnerability class D were largely affected as the inclusion of modifiers implied a half-hold change of this vulnerability class. The application of VIM confirms the notable seismic risk of the city of Sarajevo and Banja Luka due to the high vulnerability of the buildings.

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