Proceedings of the 3rd Croatian Conference on Earthquake Engineering - 3CroCEE
19–22 March 2025, Split, Croatia
Copyright © 2025 CroCEE
DOI: https://doi.org/10.5592/CO/3CroCEE.2025.53

A REVIEW OF EXISTING SEISMIC VULNERABILITY FUNCTIONS FOR BUILDINGS IN THE BALKAN REGION

Kristina Milkova [(1)], Marta Šavor Novak [(2)], Marko Marinkovic [(3)], Elena Dumova - Jovanoska[(4)]

[(1)] *Asst. prof., Chair of Theory of Structures and Computational Analysis, Department of Structural Analysis and Earthquake Engineering, Faculty of Civil Engineering Skopje, N. Macedonia, milkova@gf.ukim.edu.mk,*
[(2)] *Assoc. prof., Faculty of Civil Engineering, Department of Engineering Mechanics, University of Zagreb, Croatia, msavor@grad.hr*
[(3)] *Asst. prof., Chair of Engineering Mechanics and Theory of Structures, Faculty of Civil Engineering, University of Belgrade, Serbia; mmarinkovic@grf.bg.ac.rs*
[(4)] *prof., Chair of Theory of Structures and Computational Analysis, Department of Structural Analysis and Earthquake Engineering, Faculty of Civil Engineering Skopje, N. Macedonia, dumova@gf.ukim.edu.mk*

Abstract

This paper provides detailed investigation of the methodologies developed for seismic vulnerability assessment in the area. Empirical, analytical, and hybrid approaches that have been regionally developed and applied are summarized and their similarities and differences are discussed. Having in mind the parallels in existing structural archetypes in the region (N. Macedonia, Serbia, Bosnia and Herzegovina, Croatia, Romania, Greece), the investigation focuses on the most common types: masonry and reinforced concrete structures. A reliable assessment of seismic hazard is essential for effective vulnerability evaluation, and the relevant published methodologies are also summarized. Additionally, the developed risk assessment methodologies are discussed. This overview is expected to guide research at institutions throughout the region and encourage enhanced collaboration among experts in seismic vulnerability.

Keywords: vulnerability functions, Balkan region, hazard, analytical, empirical, hybrid

1. Introduction

The process of seismic risk assessment involves analyzing and precisely determining three key elements: hazard, exposure, and vulnerability. **Hazard** refers to the probability and characteristics of earthquake events in a given area. This includes evaluating factors such as seismic activity, fault lines, historical earthquake data, and seismic hazard analysis to assess the potential intensity and frequency of earthquakes. **Exposure** relates to the assets, population, and infrastructure at risk within the affected region. This involves identifying and quantifying elements such as buildings, critical infrastructure, cultural heritage sites, and the number of people exposed to potential earthquake hazards. **Vulnerability** focuses on the susceptibility of the exposed elements to damage or loss due to an earthquake. This requires evaluating the structural integrity of buildings, the resilience of infrastructure, and the population's preparedness to withstand and recover from an earthquake event.

By thoroughly examining these three factors, experts can gain a comprehensive understanding of the seismic risk in a specific region and develop appropriate strategies for risk reduction and management. In the context of developing a national seismic risk mitigation strategy, the availability of fragility functions for locally defined structural prototypes plays a crucial role. Fragility functions are defined as the probability of exceeding a certain level of damage for a given ground motion intensity, and they serve as a foundation for estimating seismic losses. A multidisciplinary approach, with expertise in hazard and risk estimation, is required for implementing a comprehensive seismic vulnerability evaluation procedure for buildings. The wide range of applications for existing methodologies allows for numerous proposed approaches and categorizations. The available resources and knowledge in construction, as well as local traditions and experiences across different regions, have led to the development of various building typologies since each region can be characterized by its unique buildings, built with specific materials and techniques.

Copyright © 2025 CroCEE
DOI: https://doi.org/10.5592/CO/3CroCEE.2025.53

2. Seismic hazard of Balkan region

The Balkan region is tectonically active, located at the intersection of three major plates: Eurasian, African, and Anatolian, which are further subdivided into smaller plates. The region's geodynamics are influenced by active tectonic processes in the Eastern Mediterranean, including the collision of the Adriatic (Apulian) microplate with the Dinarides, the subduction of the Ionian and Levantine oceanic lithospheres beneath the Hellenic arc-and-trench system, and the collision between Eurasia and Arabia, which drives the westward movement of Anatolia along the North Anatolian dextral strike-slip fault. These processes cause frequent, although generally minor, earthquakes [1].

The most destructive earthquake in the Balkans over the past century occurred in Skopje in July 1963, claiming over a thousand lives and injuring more than 4,000 people [2]. Recent earthquakes in North Macedonia, Albania, and Croatia emphasize the ongoing need for seismic design in new structures and seismic risk assessment of existing ones. The most recent major earthquake in North Macedonia occurred on September 10, 2016, with a magnitude of 5.2 at a depth of 10 km, 2 km northeast of Skopje [3]. The event injured over 50 people and caused significant damage to buildings.

The Croatian coast experiences a range of small to large earthquakes. In 2020, Croatia was struck by a series of significant earthquakes, particularly in the northern part of the country near Zagreb. That year, a magnitude 6.4 earthquake struck Petrinja on December 29, 2020, drawing attention from seismologists. Earlier, in March 2020, Zagreb experienced a 5.4 magnitude earthquake that caused considerable damage and one fatality [4].

Figure 1 illustrates earthquakes with a magnitude greater than 5.5 that have occurred from 1900 to the present.

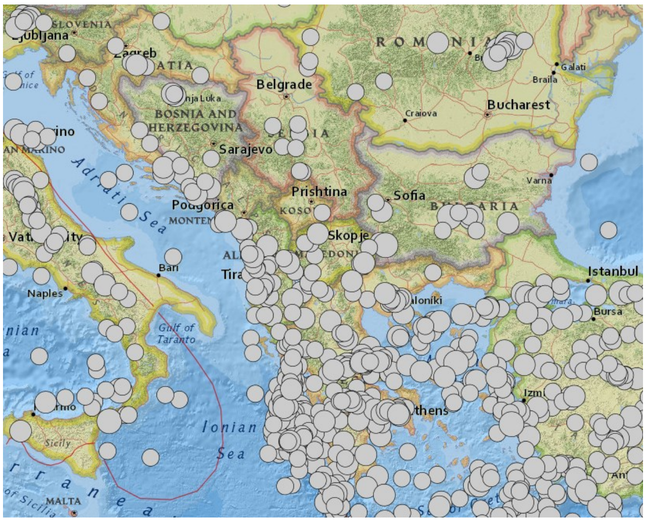

Figure 1. Map of earthquakes 1900 – 2025, M>5.5, USGS

In Bosnia and Herzegovina, the most significant recent earthquake took place on April 22, 2022. A magnitude 5.7 earthquake struck 42 kilometers southeast of Mostar, causing one fatality and substantial property damage. The earthquake was also felt along the Croatian coast, in Montenegro, and further southeast in Albania [5].

While earthquakes are frequent, significant ones are rare but still happen and can cause minor damage to sturdy homes in Serbia. A notable recent earthquake, with a magnitude of 5.4, struck central Serbia near Kraljevo on November 3, 2010. The shaking was felt throughout the country, including the capital, Belgrade, and in neighboring countries. Many buildings were also damaged, with over 1,500 being deemed unsafe for occupancy [6].

Romania ranks as one of the most affected countries in Europe in terms of the number of fatalities caused by earthquake disasters in the 20th century, including deaths from single events. One significant

Copyright © 2025 CroCEE
DOI: https://doi.org/10.5592/CO/3CroCEE.2025.53

event was the March 4, 1977 earthquake, which resulted in 1,578 deaths, of which 90% occurred in Bucharest [7].

Greece often hosts large magnitude earthquakes, whilst a moderate or small magnitude earthquake is felt every 2-3 days on average. Although most of these earthquakes with low-intensity, a few cases have been recorded as devastating for the human environment or for life loss (e.g. the 1881 Chios, 1953 Kefalonia, 1999 Athens earthquakes). The Great Thessaloniki earthquake occurred on 20 June at 23:03 local time. The shock registered 6.2 on the moment magnitude scale, had a maximum Mercalli intensity of IX (Violent), and was felt throughout northern Greece, former Yugoslavia and Bulgaria [8].

One of the most recent significant studies addressing specifically the seismic hazard in the Western Balkans was conducted as part of the Harmonization of Seismic Hazard Maps in the Western Balkan Countries Project (BSHAP) [9]. The main outcome of BSHAP is the creation of new probabilistic seismic hazard maps for the Western Balkans, developed using the smoothed-gridded seismicity approach. The results are presented in terms of peak horizontal acceleration (PGA) for 95- and 475-year return periods, in accordance with Eurocode 8 requirements.

Considering the seismic hazard in the region and the relatively similar construction practices in the past, it would be highly valuable to establish a database that links structural typologies to vulnerability functions. This would enhance preparedness for future seismic events across a broader area.

3. Existing seismic vulnerability functions in the Balkan Region

This paper's main aim is to present an overview of the seismic vulnerability studies conducted in the Balkan region. Given the shared construction practices across the countries in the region, the objective is to outline the current state of knowledge, which can serve as a foundation for future risk assessments. The classification of seismic vulnerability analysis methods is based on Calvi [10]. Several studies from North Macedonia, Croatia, Serbia, Bosnia and Herzegovina, Romania, and Greece are reviewed, with key findings related to seismic hazard, building types, and the methods used in these studies summarized.

3.1.Republic of N. Macedonia

Researchers in the Republic of North Macedonia have been closely following global advancements in this field since its inception. Specifically, Nochevski, in his PhD research under the supervision of Petrovski, proposed an original methodology for the empirical and analytical calculation of vulnerability curves. Two representative types of **reinforced concrete frames** were analyzed. Peak acceleration of **selected earthquake records** (Ulcinj, Bar, El Centro) have been varied from very low levels up to 0.40g. The integral structure is represented by shear type model. **Vulnerability curves** for structural and nonstructural elements were developed. [11]

Dumova– Jovanoska in her Phd research proposes an analytical methodology for expressing the relationship damage– earthquake intensity in the forms of vulnerability curves and damage probability matrices. A set of **240 synthetic time histories** were generated for local seismic hazard representation. The proposed method is applied on **reinforced concrete frame-wall structures (lower and higher than 10 stories)**. Two sets of **fragility curves** and damage probability matrices were defined. [12]

Within the framework of the RISK-UE Project [13], an approach was proposed for developing the seismic vulnerability of **reinforced concrete structures**, which are the dominant new residential building type in the Republic of North Macedonia. Databases from the **1979 Montenegro earthquake and the 1994 Bitola earthquake** were used as seismic input for the nonlinear dynamic time-history analysis of a 1D shear-type lumped mass model, which was employed to simulate the RC structures. Five damage grades were adopted, and capacity and fragility curves were generated.

Twenty individual **reinforced concrete residential str**uctures for family housing and collective residential buildings were considered, divided into 3 categories according to number of stories in the frame of the research of Jakupi [14]. Nonlinear static "pushover" analysis as a procedure for assessment

Proceedings of the 3rd Croatian Conference on Earthquake Engineering - 3CroCEE
19–22 March 2025, Split, Croatia
Copyright © 2025 CroCEE
DOI: https://doi.org/10.5592/CO/3CroCEE.2025.53

of the seismic response of reinforced concrete buildings was carried out and values of the **vulnerability indices** of the buildings are obtained within the limits of 0,2 to 0,4.

In the research of Milkova, **Scenario-based Neo Deterministic Seismic Hazard Approach** [15] is used. Existing **masonry structures** are selected, each of them chosen to represent a class of similar buildings. The non - linear capacity curves of a single wall are calculated based on the shear and bending resistances according to EC. Sets of **fragility curves** for class of structures were developed [16]

Volchev et al [17] considers six **reinforced concrete three-bay frames** with varying numbers of stories (2, 3, 5, 7, 10, and 13 stories) and two types of infill (strong and weak). Nonlinear dynamic analysis for the defined mathematical models is performed for 14 earthquake records. **Five series of vulnerability curves** are obtained, namely: a series for structures with less than 6 stories, a series for structures with more than 6 stories, a series for structures with weak infill, a series for structures with strong infill, and a series for all analyzed structures.

Research of Zlateski [18] focuses on **unreinforced stone and brick masonry structures** constructed before the introduction of a more demanding seismic design code. The **vulnerability index** is obtained by the calculation of a score as the weighted sum of 14 characteristic parameters related to the building's seismic response and distributed into vulnerability classes, providing initial seismic vulnerability assessment by using simplified scoring method.

3.2. Bosnia and Herzegovina

Research in Bosnia and Herzegovina primarily focuses on methods for rapid building assessment. In [19], the iRapid methodology is employed, considering factors such as building construction age, materials, number of stories, population density, and peak ground acceleration (PGA). Each element is evaluated based on its frequency and represented by a lognormal distribution function. The results indicate that cities with lower PGA and higher population density may face disasters they are unprepared for.

In [20], the macroseismic method derived from the EMS 98 scale is used. This study includes a selection of **unreinforced and confined masonry buildings** in Sarajevo and Banja Luka. The **vulnerability index** is calculated based on the building type, regional vulnerability factor, and behavior modifier factor. Using this index and the proposed ductility index, the average degree of damage for each building is developed for three levels of earthquake intensity, and vulnerability curves are plotted.

The analysis for Tuzla [21] focuses on **earthquake intensities VII and VIII** for seismic risk assessment of structures in the area. The study includes all buildings in Tuzla, **including reinforced concrete, unreinforced masonry with flexible and rigid floors, and confined structures**. The RISK UE category matrix is used to classify the buildings, and the vulnerability index is calculated using the macroseismic method, based on building type, regional vulnerability factors, and behavior modifiers. Damage probability matrices and **vulnerability curves** are generated for all the selected building topologies.

In Visoko [22], **earthquake intensities VI and VII are considered** to determine the seismic risk for buildings. The study analyzes three types **of masonry structures** from a database of 94 buildings. The **vulnerability index** is based on building topology, behavior modifiers, and regional modifiers. The mean damage grade is calculated based on the vulnerability index and macroseismic intensity.

Seismic hazard intensities VII and VIII are applied in an analysis of 105 **unreinforced masonry and concrete buildings** across two municipalities in Sarajevo [23]. The **vulnerability index** here is calculated based on structural behavior modifiers (such as the number of floors, plan irregularity, and type of roof) and regional modifiers. The mean damage grade is calculated based on the vulnerability index, macroseismic intensity, and ductility index.

Copyright © 2025 CroCEE
DOI: https://doi.org/10.5592/CO/3CroCEE.2025.53

3.3. Croatia

An overview of various methodologically diverse risk assessments, including isolated individual initiatives, is provided in [24]. In their 2019 research, it is concluded that the level of awareness regarding Croatia's exposure and vulnerability to earthquakes is insufficiently developed. This lack of awareness undermines efforts to promote institutionalized seismic risk assessment, mitigation, and preparedness activities.

The seismic fragility assessment of **masonry-infilled reinforced concrete frames** was analyzed in research by Grubišić et al. [25]. The study utilized three model structures with different infill configurations. Probabilistic fragility curves were developed and interpreted using Incremental Dynamic Analysis (IDA) with a **set of seven earthquake records**. The results are presented as median values of the **fragility curves for four distinct limit states**, providing insight into the performance of such structural systems under seismic loading.

In the research by Hadzima-Nyarko [26], two methods for earthquake vulnerability assessment are applied and compared. The first method is a relatively simple and fast approach developed by Croatian researchers, which uses the **Damage Index (DI)** as a numerical indicator of structural damage levels. The second method used in the research is the **Macroseismic method**.

A case study on seismic risk assessments is presented using Croatian cities to provide an overview of the **relative seismic risk in Croatia** [27], based on general parameters derived from Census data. The vulnerability of buildings described in this paper is determined by the weighted sum of eight impact factors associated with the construction age, each multiplied by a corresponding weight which reflects the relative significance of each factor.

The methodology proposed in the SERA project for developing fragility and consequence models for European buildings has been applied to the building inventory in Croatia [28]. The framework's basic workflow begins with defining the **Building Class Information Model**, which incorporates all the necessary information to calculate the total variability of the fragility function associated with a specific building class.

The development of fragility curves for fourteen of the **most common structural systems** in Zagreb is detailed in research by Novak et al. [29]. Fragility curves were generated for each building type, including masonry and reinforced concrete buildings, using the macroseismic method in alignment with the RISK-UE Project framework. Seismic hazard data, specifically **peak ground acceleration (PGA)** values for Zagreb, served as input for the vulnerability assessments. The damage probability matrix was initially derived as discrete values and then fitted to a lognormal cumulative probability distribution to obtain **continuous fragility functions**, providing a comprehensive assessment of building vulnerability in the region.

Calculation of seismic vulnerability based on the expected behavior of the building, obtained by overlapping the demand curve and capacity curve applied to **traditional unreinforced masonry buildings** of the city Osijek is done in the research of Pavic et al [30]. The values of spectral displacement obtained for the performance point of a specific building class are used as the input parameters for the **fragility curve** for different levels of damage.

The activities in Croatia following the two earthquakes in 2020 have shown that the seismic vulnerability of the exposed building stock is a major problem.

The research by Demšić et al. [31] evaluates both the in-plane and out-of-plane seismic response of an existing **unreinforced masonry row aggregate located in the historic center of Zagreb's Lower Town**. Particular emphasis is placed on the selection of ground motion records for non-linear dynamic analyses, ensuring they are adapted to the **local seismic hazard**. Fragility curves for each damage mode were generated using the R2R software, applying the least squares fit method to estimate the probability of damage under varying seismic intensities.

Copyright © 2025 CroCEE
DOI: https://doi.org/10.5592/CO/3CroCEE.2025.53

The work of Pilipović [32] contributes to the development of new vulnerability models for typical buildings in Zagreb, Croatia. A representative **unreinforced masonry mid-rise building** with solid brick shear walls was selected as the focus of the study. To generate fragility curves, the multiple stripes analysis approach was employed. On-site seismic hazard was calculated using a **probabilistic seismic hazard assessment** aligned with the national seismic hazard assessment methodology.

These studies ([31] and [32]) were carried out in scope of the 2BESAFE research project (New vulnerability models of typical buildings in urban areas: applications in seismic risk assessment and target retrofitting methodology), funded by the Croatian Science Foundation (https://2besafe.grad.hr/).

3.4. Serbia

In recent research by Blagojevic et al. [33], a novel building classification system was developed for Serbia's residential building stock. This classification is based on **existing building taxonomies** but has been adapted to reflect local building characteristics. Evidence from the performance of common building typologies during past earthquakes in Serbia and the region, along with collective expert knowledge, was utilized to develop **expert-based seismic fragility functions** for these typologies. To derive the fragility functions MCS earthquake intensities were transformed into **peak ground acceleration (PGA)** values. Expert judgments were then statistically analyzed for each PGA value to determine the probabilities of reaching or exceeding specific damage states.

The newly utilized Adriseismic Methodology in Serbia [34] for **Expeditious Seismic Assessment** is developed both for unreinforced masonry and reinforced concrete. Regarding masonry buildings, it focuses on three primary seismic failure mechanisms: masonry disintegration, out-of-plane failure, and in-plane damage or failure. The key parameter for evaluating the seismic behavior of a structure is the **Index of Structural Response**, which is calculated to assess the building's performance under seismic loads. Based on this parameter, seismic risk categories are proposed, offering a framework for classifying the vulnerability of such structures.

The seismic vulnerability of **school buildings** is the focus of research by Marinković et al. [35]. This study introduces a new seismic risk methodology called MM Risk and provides a comparative analysis with the Adriseismic methodology used for seismic risk assessment. Through a review of the existing literature and the application of both methods to a dataset of 213 schools (comprising 367 buildings), the paper evaluates the strengths and limitations of each methodology in terms of accuracy, complexity, and practical usability. A seismic hazard map for Serbia, indicating peak ground acceleration (**PGA) values for earthquakes with a 10% probability of exceedance in 50 years**, was utilized in accordance with Eurocode 8 requirements.

3.5. Romania

The initial data on vulnerability of buildings in Bucharest were obtained from a **post-earthquake survey** conducted following the March 4, 1977, earthquake. This survey analyzed a sample of over **18,000 buildings located in various parts of the city**. The results allowed for the derivation of statistical damage spectra for several sub-areas of Bucharest. These findings were further processed to develop vulnerability functions expressed as conditional damage distributions [36].

One of the first attempt of development of a nationwide seismic vulnerability estimation system, concerning basically the existing building stock was done in frame of two projects, referred to as: AC3, Consultancy services for development of a Vrancea earthquake scenario and AC6, Consultancy services for integrated disaster risk management study [36]. The approach adopted relied primarily on the definition of relevant categories of buildings, that are specific to Romania, categorized according to the material and structural system, height, period of construction.

According to [37], the **seismic risk in Bucharest** is well defined, with the most vulnerable structures identified as mid-and high-rise buildings constructed before the implementation of the 1978 earthquake-resistant design code. Buildings constructed prior to 1941 were designed without accounting for earthquake forces, while those built between 1941 and 1978 were designed using a spectrum that was

Copyright © 2025 CroCEE
DOI: https://doi.org/10.5592/CO/3CroCEE.2025.53

inadequate for mid- and high-rise buildings, given the characteristics of the strong ground motions recorded during the 1977 and 1986 earthquakes. After 1989, the Romanian government and local authorities initiated a national program to evaluate the seismic resistance of vulnerable buildings. This program is later incorporated into a broader national strategy for seismic risk reduction.

HAZUS and ATC-40 methodologies are used for seismic vulnerability assessment of reinforced concrete (RC) in [37]. Five case studies involving **representative residential buildings in Bucharest**, the capital city of Romania, are analyzed and compared. The paper also emphasizes the unique characteristics of the **demand spectra in Bucharest**, which differ significantly from those used in HAZUS.

A seismic vulnerability evaluation of buildings within an urban sector of Timișoara was conducted using the **EMS-98 macroseismic approach** [38]. The typological vulnerability classes of buildings were defined according to the RISK-UE method, allowing for classification from both typological and structural perspectives. A parametric analysis was performed by **varying the seismic magnitude** and the site-source distance to estimate potential seismic losses under different earthquake scenarios.

Another research in Romania is focused on Iași—one of Romania's major cities exposed to earthquakes originating in the Vrancea area—aims to assess seismic vulnerability through a multi-criteria analysis of building infrastructure and social vulnerability. The analysis incorporates several indicators, including physical factors (characteristics of buildings and terrain), social factors (population and economic income), and accessibility to emergency services and hospitals. By summing the weighted values of the standardized indicators, an integrated **seismic vulnerability index** was derived. [39]

A significant new study on the **analytical** derivation of **seismic fragility curves** was conducted in Romania, as shown in [40][41][42]. The seismic fragility assessment in the research of Pavel et al [40] was carried out using **incremental dynamic analysis** for **high-rise reinforced concrete (RC) frame structures**, as well as for **high-rise RC shear wall structures,** which are commonly used in residential buildings. Incremental dynamic analysis was performed with **ground motion datasets specific to the seismic conditions of Romania**.

3.6. Greece

One of the earliest vulnerability assessment methodologies in Greece was introduced in 1998 [43], combining elements of both empirical and analytical approaches. This **hybrid methodology** utilized **probability damage matrices**, which were integrated into a cost-benefit model designed to assess the feasibility of seismic retrofitting for the existing stock **of reinforced concrete buildings in Thessaloniki**, Greece. The losses estimated using the proposed procedure were found to align closely with the actual losses incurred during the 1978 Thessaloniki earthquake.

Seismic vulnerability and collapse probability assessment of buildings in Greece, covering **all common typologies** was done in the research of Pomonis et al [44]. Two distinct methodologies are presented for estimating the collapse probability of various building types **across typical Modified Mercalli Intensity (MMI) levels (VI to IX).** The first approach relies entirely on the statistical analysis of data from past earthquakes in Greece, while the second employs hybrid vulnerability curves that combine analytical and empirical data.

The observational data used in the research of Eleftheriadou and Karabinis [45] were collected from post-earthquake surveys conducted in the region affected by the **September 7, 1999 Athens earthquake**. Following analysis, a unified damage database was compiled, encompassing 180,945 damaged buildings in the earthquake's near-field area. These buildings are categorized into various **structural types based on materials, seismic codes, and construction techniques** characteristic of Southern Europe. **Damage probability matrices (DPMs) and vulnerability curves** were developed for specific structural types, offering valuable insights into their seismic performance.

The **hybrid approach** for seismic vulnerability assessment, developed at Aristotle University of Thessaloniki [46], is characterized by its integration of **statistical data with processed results from**

Copyright © 2025 CroCEE
DOI: https://doi.org/10.5592/CO/3CroCEE.2025.53

nonlinear dynamic or static analyses. This combination enables the extrapolation of statistical data to peak ground accelerations (PGAs) and/or spectral displacements for which direct data is unavailable. The methodology utilizes **two types of earthquake scenarios**. This research addresses **both reinforced concrete (R/C) and unreinforced masonry (URM) buildings,** emphasizing that different analytical methods are more suitable for each type.

A comprehensive database documenting observed damage to Greek reinforced concrete (**RC) and unreinforced masonry (URM) buildings** was used in the research of Pomonis et al [47]. These surveys covered four moderate-magnitude **earthquakes that occurred between 1986 and 2003**, encompassing **data on 28,747 buildings**. This database was used for the derivation of **vulnerability curves based on observed damage**, enabling the relative vulnerability of **10 common structural types in Greece** to be characterized.

Recent studies conducted by a group from the Department of Civil Engineering at Aristotle University, Thessaloniki, Greece, focus on the vulnerability assessment of school buildings [48][49]. Building-specific **fragility and vulnerability curves** were derived for three **reinforced concrete (RC) school buildings** based on **3D incremental dynamic analysis (IDA)** [50] of calibrated numerical models. These curves were then compared with existing generic fragility curves, and the differences were discussed. Given the high computational cost in the process of analytical derivation of fragility curves, a recent paper was published addressing the optimization of ground motions and intensity levels required, without compromising accuracy [51].

4. Summary and Conclusion

A summary of research discussed above is presented in Table 1. This table consolidates key information, offering an overview of the methodologies categorized according to Calvi [10], as referenced in the preceding discussion.

It is worth noting that the first seismic vulnerability functions for buildings in the Balkans were determined as early as the early 1990s in North Macedonia. However, despite this, there followed a period during which such research was absent. Nevertheless, the earthquakes that caused more serious damage in the past decade have reignited researchers' interest in the topic of seismic risk assessment, including the development of vulnerability functions.

4.1. Methodology

When considering the methodologies applied, the dominance of empirical methods in defining vulnerability functions is evident. This is likely due to their practicality: they neither require complex nonlinear analyses nor extensive computational resources, while enabling the assessment of many buildings. Additionally, the availability of earthquake damage data supports the widespread use of empirical methods. These methods are particularly suitable for pre-code structures, which remain prevalent in many Balkan countries.

Examining experiences across individual countries reveals notable trends. In North Macedonia, analytical methods are predominantly used, while Bosnia and Herzegovina and Serbia have relied exclusively on empirical methods to date. In Croatia, the devastating earthquakes in Zagreb and Petrinja have increased efforts to reduce seismic risk, leading to an increasing number of studies on vulnerability functions that employ empirical, analytical, and hybrid methods. Similarly, first research in this subject in Romania explore empirical methods, influenced by the catastrophic 1977 earthquake, later, in beginning of twenties of this century research dealing with RC structures designed according old codes applying analytical methods is performed.

It is worth highlighting the case of Greece, where several earthquakes from the late twenty and early twenty-first centuries, with recorded significant and well-documented damages, enabled the application of empirical methods for defining vulnerability models as early as the 1990s. However, the methodology proposed by researchers from the University of Thessaloniki is particularly valuable, combining the strengths of empirical methods, a large number of well-documented damages to

Copyright © 2025 CroCEE
DOI: https://doi.org/10.5592/CO/3CroCEE.2025.53

buildings from earthquakes, and the possibilities provided by analytical methods (nonlinear analysis) for filling in the gaps in documented damages.

Table 1. Summary of analyzed research

		Republic of North Macedonia	**Bosnia and Herzegovina**	**Croatia**	**Serbia**	**Romania**	**Greece**
empirical	**index**	Zlateski, 2020 [18]	Ademović et al ,2020 [19] Ademović et al, 2022[22] Ademović et al, 2022 [23]	Atalić et al, 2019 [24] Hadzima-Nyarko et al, 2017 [26] Šipoš et al, 2017 [27] Nikolic et al, 2021 [53]	Marinkovic et al. 2023, [35] Predari et al. 2024, [34]	Chieffo et al, 2019 [38] Banica et al, 2017 [39]	
	curves		Ademović et al, 2020 [20] Ademović et al, 2022 [21]	Moretic et al, 2023 [52]	Blagojevic et al, 2023, [33]	Sandi et al, 2007, [36]	Eleftheriadou et al, 2011 [45] Pomonis et al, 2014 [47]
analytical	**pushover**	Milkova et al, 2020 [16] Jakupi, 2015 [14]		Crowley et al, 2019 [28] Pavic et al, 2019 [30]		Vacareanu et al, 2004 [37]	
	dynamic	Dumova-Jovanoska, E., 2000 [12] Nocevski, 1993 [11] Milutinovic et al., 2003 [13] Volcev, 2024 [17]		Demsic et al, 2024 [31] Grubisicet al, 2013 [25] Novak et al, 2019 [29] Pilipovic et al, 2024 [32]		Pavel et al, 2021 [40] Olteanu et al, 2016 [41] Pavel et al, 2019 [42]	Fotopoulou et al, 2023 [48] Karafagka et al, 2024 [49]
hybrid				Nikolic et al, 2022 [54]			Kappos et al (1998) [43] Pomonis et al, (2009) [44] Kappos, A. J. (2013). [46]

4.2. Hazard

As expected, empirical methods utilize hazard data from macroseismic maps, such as those included in seismic design regulations like MCZ and EMS-98. Conversely, analytical methods based on dynamic analysis rely on records from actual earthquakes, with one notable exception: a study conducted in Skopje that used synthetic earthquakes generated based on local conditions. In one method employing nonlinear static analysis, region-specific response spectra were applied, derived using a neodeterministic approach for selected regions of North Macedonia or the entire country.

Copyright © 2025 CroCEE
DOI: https://doi.org/10.5592/CO/3CroCEE.2025.53

4.3. Constructions classes

Regarding the classes of structures for which vulnerability functions were determined, residential buildings constructed of masonry and reinforced concrete were predominantly analyzed. As expected, empirical methods are mainly applied to pre-code structures and reinforced concrete buildings designed according to older regulations.

4.4. Conclusion

Without claiming to be exhaustive, the authors aim to provide an overview of the existing approaches to defining vulnerability functions that consider the specific hazards and construction practices across the Balkan Peninsula. It is anticipated that this overview will help guide research in various institutions throughout the region, foster greater collaboration among seismic vulnerability experts, and contribute to the creation of a more effective European model for assessing seismic risk.

References

[1] D'Agostino, N., Copley, A., Jackson, J., Koçi, R., Hajrullai, A., Duni, L., & Kuka, N. (2022). Active tectonics and fault evolution in the Western Balkans. Geophysical Journal International, 231(3), 2102-2126.

[2] Abolmasov, B., Jovanovski, M., Ferić, P., & Mihalić, S. (2011). Losses due to historical earthquakes in the Balkan region: Overview of publicly available data. Geofizika, 28(1), 161-181.

[3] Sinadinovski, C., & Cernih, D. (2019, January). Analysis of records from the M5. 2 September 2016 Skopje earthquake. In Geophysical Research Abstracts (Vol. 21).

[4] Government of Croatia, & World Bank. (2021). Croatia December 2020 Earthquake—Rapid Damage and Needs Assessment.

[5] Euronews. 2022. Earthquake in Bosnia Kills One, Causes Significant Damage Across Several Cities. Accessed on 06-Jul-2022. Available at: https://www.euronews.com/2022/04/23/earthquake-in-bosnia-kills-one-causes-significant-damage-across-several-cities

[6] Marinković, D., Stojadinović, Z., Kovačević, M., & Stojadinović, B. (2018). 2010 Kraljevo Earthquake Recovery Process Metrics Derived from Recorded Reconstruction Data. In 16th European Conference on Earthquake Engineering.

[7] Georgescu, E. S., & Pomonis, A. (2008, October). The Romanian earthquake of March 4, 1977 revisited: New insights into its territorial, economic and social impacts and their bearing on the preparedness for the future. In Proceedings of the 14th World Conference on Earthquake Engineering, Beijing, China (pp. 12-17).

[8] Kouskouna, V., & Makropoulos, K. (2004). Historical earthquake investigations in Greece. Annals of Geophysics, 47(2-3).

[9] Salic, R., Sandikkaya, M. A., Milutinovic, Z., Gulerce, Z., Duni, L., Kovacevic, V., ... & Stanko, D. (2017). BSHAP project strong ground motion database and selection of suitable ground motion models for the Western Balkan Region. Bulletin of earthquake engineering, 15, 1319-1343.

[10] Calvi, G. M., Pinho, R., Magenes, G., Bommer, J. J., Restrepo-Vélez, L. F., & Crowley, H. (2006). Development of seismic vulnerability assessment methodologies over the past 30 years. ISET journal of Earthquake Technology, 43(3), 75-104.

[11] Nocevski NK. Definition of empirical and theoretical models for assessment of vulnerability level in high rise buildings. Doctoral thesis. IZIIS, Skopje, 1993.

[12] Dumova-Jovanoska, E. (2000). Fragility curves for reinforced concrete structures in Skopje (Macedonia) region. Soil Dynamics and Earthquake Engineering, 19(6), 455-466.

[13] Milutinovic, Z. V., & Trendafiloski, G. S. (2003). Risk-UE An advanced approach to earthquake risk scenarios with applications to different European towns. Contract: EVK4-CT-2000-00014, WP4: Vulnerability of current buildings, 1-111.

[14] Jakupi, E., Denkovska, L., & Dumova-Jovanoska, E. (2015). Seismic Vulnerability of Rc Buildings in Polog Valley. International scientific jurnal "Micro, Macro & Mezzo Geo Information, 5, 004-0.

Copyright © 2025 CroCEE
DOI: https://doi.org/10.5592/CO/3CroCEE.2025.53

[15] Dumova-Jovanoska, E., & Milkova, K. (2022). NDSHA-based vulnerability evaluation of precode buildings in Republic of North Macedonia: novel experiences. In Earthquakes and Sustainable Infrastructure (pp. 455-474). Elsevier.

[16] Milkova, K., Butenweg, C., & Dumova-Jovanoska, E. (2020). Methodology for Development of Seismic Vulnerability Curves for Existing Unreinforced Masonry buildings. In 17th World Conference on Earthquake Engineering, Sendai, Japan.

[17] Volcev, R., Postolov, N., Milkova, K., Todorov, K., & Dumova-Jovanoska, E. (2024). Seismic vulnerability of masonry infilled rc frames with an open first story, 18WCEE, Milan, Italy

[18] Zlateski, A., & Shendova, V. Harmonization of seismic vulnerability assessment of urban historic centers.

[19] Ademović, N., Kalman Šipoš, T., & Hadzima-Nyarko, M. (2020). Rapid assessment of earthquake risk for Bosnia and Herzegovina. Bulletin of earthquake engineering, 18, 1835-1863.

[20] Ademović, N., Hadzima-Nyarko, M., & Zagora, N. (2020). Seismic vulnerability assessment of masonry buildings in Banja Luka and Sarajevo (Bosnia and Herzegovina) using the macroseismic model. Bulletin of earthquake engineering, 18, 3897-3933.

[21] Ademovic, N., Hadzima-Nyarko, M., & Zagora, N. (2022). Influence of site effects on the seismic vulnerability of masonry and reinforced concrete buildings in Tuzla (Bosnia and Herzegovina). Bulletin of earthquake engineering, 20(5), 2643-2681.

[22] Ademović, N., Hadzima-Nyarko, M., Zagora, N., Piljug, A., & Medanović, Ć. (2022, June). Vulnerability of Residential Buildings in Sarajevo, BIH. In International Symposium on Innovative and Interdisciplinary Applications of Advanced Technologies (pp. 3-14). Cham: Springer International Publishing.

[23] Ademović, N., Hadzima-Nyarko, M., Zagora, N., Piljug, A., & Medanović, Ć. (2022, June). Vulnerability of Residential Buildings in Sarajevo, BIH. In International Symposium on Innovative and Interdisciplinary Applications of Advanced Technologies (pp. 3-14). Cham: Springer International Publishing.

[24] Atalić, J., Šavor Novak, M., & Uroš, M. (2019). Seismic risk for Croatia: Overview of research activities and present assessments with guidelines for the future. Građevinar, 71(10), 923-947.

[25] Grubišić, M., Kalman Šipoš, T., & Sigmund, V. (2013). Seismic fragility assessment of masonry infilled reinforced concrete frames. 50th SE-EEE: Skopje, North Macedonia.

[26] Hadzima-Nyarko, M., & Kalman Sipos, T. (2017). Insights from existing earthquake loss assessment research in Croatia. Earthquakes and structures, 13(4), 365-375.

[27] Šipoš, T. K., & Hadzima-Nyarko, M. (2017). Relative rapid seismic risk assessment. International journal of disaster risk reduction, 24, 348-360.

[28] Crowley, H., Silva, V., Despotaki, V., Martins, L., & Atalić, J. (2019, October). European Seismic Risk Model 2020: Focus on Croatia. In Proceedings of Scientific Symposium "Future Trends in Civil Engineering", Zagreb, Croatia (pp. 83-101).

[29] Novak, M. Š., Atalic, J., Uroš, M., Prevolnik, S., & Nastev, M. (2019, October). Seismic risk reduction in Croatia: mitigating the challenges and grasping the opportunities. In Scientific Symposium FUTURE TRENDS IN CIVIL ENGINEERING Zagreb, Croatia (pp. 72-109).

[30] Pavić, G., Hadzima-Nyarko, M., Plaščak, I., & Pavić, S. (2019). Seismic vulnerability assessment of historical unreinforced masonry buildings in Osijek using capacity spectrum method. Acta Phys. Pol. A, 135(5), 1138-1141.

[31] Demsic, M., Pinasco, S, Pilipović, A., Cattari, S., Lagomarsino, S., Šavor Novak, M. & Uroš, M. (2024), Development of fragility curves of masonry buildings build in a regular row aggregate, 18WCEE, Milan, Italy

[32] Pilipović, A., Jevtić Rundek, R., Uroš M., Šavor Novak, M., Demšić, M., Prevolnik, S., (2024), New vulnerability model of a typical unreinforced masonry building in the urban area of Zagreb, 18WCEE, Milan, Italy.

[33] Blagojević, N., Brzev, S., Petrović, M., Borozan, J., Bulajić, B., Marinković, M., ... & Stojadinović, B. (2023). Residential building stock in Serbia: classification and vulnerability for seismic risk studies. Bulletin of earthquake engineering, 21(9), 4315-4383.

[34] Predari, G., Stefanini, L., Marinković, M., Stepinac, M., & Brzev, S. (2023). Adriseismic methodology for expeditious seismic assessment of unreinforced masonry buildings. Buildings, 13(2), 344.

[35] Marinković, M., Bošković, M., Đorđević, F., Krtinić, N., & Žugić, Ž. (2024). Seismic Risk Assessment in School Buildings: A Comparative Study of Two Assessment Methods. Buildings, 14(8), 2348.

[36] Sandi, H., Pomonis, A., Francis, S., Georgescu, E. S., Mohindra, R., & Borcia, I. S. (2007). Seismic vulnerability assessment: Methodological elements and applications to the case of Romania.

[37] Vacareanu, R., Radoi, R., Negulescu, C., & Aldea, A. (2004, August). Seismic vulnerability of RC buildings in Bucharest, Romania. In 13thWorld Conference on Earthquake Engineering, Vancouver, Canada.

[38] Chieffo, N., Mosoarca, M., Formisano, A., & Apostol, I. (2019, February). Seismic vulnerability assessment and loss estimation of an urban district of Timisoara. In IOP Conference Series: Materials Science and Engineering (Vol. 471, No. 10, p. 102070). IOP Publishing.

[39] Banica, A., Rosu, L., Muntele, I., & Grozavu, A. (2017). Towards urban resilience: A multi-criteria analysis of seismic vulnerability in Iasi City (Romania). Sustainability, 9(2), 270.

[40] Pavel, F., Vacareanu, R., & Scupin, A. (2021). Seismic fragility assessment for post-1977 high-rise reinforced concrete structures in Romania. *Bulletin of Earthquake Engineering*, *19*, 6521-6544.

[41] Olteanu, P., Coliba, V., Vacareanu, R., Pavel, F., & Ciuiu, D. (2016). Analytical seismic fragility functions for dual RC structures in Bucharest. In *The 1940 Vrancea Earthquake. Issues, Insights and Lessons Learnt: Proceedings of the Symposium Commemorating 75 Years from November 10, 1940 Vrancea Earthquake* (pp. 463-479). Springer International Publishing.

[42] Pavel, F., & Carale, G. (2019). Seismic assessment for typical soft-storey reinforced concrete structures in Bucharest, Romania. *International Journal of Disaster Risk Reduction*, *41*, 101332.

[43] Kappos, A. J., Stylianidis, K. C., & Pitilakis, K. (1998). Development of seismic risk scenarios based on a hybrid method of vulnerability assessment. Natural Hazards, 17, 177-192.

[44] Pomonis, A., Kappos, A., Karababa, F., & Panagopoulos, G. (2009). Seismic vulnerability and collapse probability assessment of buildings in Greece. Second International Workshop on Disaster Casualties 15-16 June 2009, University of Cambridge, UK

[45] Eleftheriadou, A. K., & Karabinis, A. I. (2011). Development of damage probability matrices based on Greek earthquake damage data. Earthquake Engineering and Engineering Vibration, 10, 129-141.

[46] Kappos, A. J. (2013). Seismic vulnerability and loss assessment for buildings in Greece. Seismic Vulnerability of Structures, 111-160.

[47] Pomonis, A., Gaspari, M., & Karababa, F. S. (2014). Seismic vulnerability assessment for buildings in Greece based on observed damage data sets. Bollettino di Geofisica Teorica ed Applicata, 55(2).

[48] Fotopoulou, S., Karafagka, S., Petridis, C., Manakou, M., Riga, E., & Pitilakis, K. (2023). Vulnerability assessment of school buildings: Generic Versus building-specific fragility curves. *Journal of Earthquake Engineering*, *27*(11), 2994-3023.

[49] Karafagka, S., Riga, E., Oikonomou, G., Karatzetzou, A., Fotopoulou, S., Pitilakis, D., & Pitilakis, K. (2024). RiskSchools: a prioritization-based system for the risk assessment of school buildings combining rapid visual screening smartphone app and detailed vulnerability analysis. *Bulletin of Earthquake Engineering*, *22*(6), 2951-2980.

[50] Vamvatsikos, D., & Cornell, C. A. (2002). Incremental dynamic analysis. Earthquake engineering & structural dynamics, 31(3), 491-514.

[51] Sipcic, N., de Quevedo Iñarritu, P. G., Kohrangi, M., Vamvatsikos, D., & Bazzurro, P. (2024). Practical Approach to Hazard-Consistent Fragility Curve Estimates Using Bayesian Updating. Available at SSRN 5033487.

[52] Moretić, A., Chieffo, N., Stepinac, M., & Lourenço, P. B. (2023). Vulnerability assessment of historical building aggregates in Zagreb: implementation of a macroseismic approach. Bulletin of earthquake engineering, 21(4), 2045-2065.

[53] Nikolić, Ž., Runjić, L., Ostojić Škomrlj, N., & Benvenuti, E. (2021). Seismic vulnerability assessment of historical masonry buildings in Croatian coastal area. Applied Sciences, 11(13), 5997.

[54] Nikolić, Ž., Benvenuti, E., Runjić, L., Kozulić, V., & Škomrlj, N. O. (2022). Assessment of seismic vulnerability of existing masonry buildings in urban area Pula.