Proceedings of the 3rd Croatian Conference on Earthquake Engineering - 3CroCEE
19–22 March 2025, Split, Croatia

DOI: https://doi.org/10.5592/CO/3CroCEE.2025.4

A STATE-OF-THE-ART REVIEW: SEISMIC VULNERABILITY ASSESSMENT METHODS FOR MASONRY STRUCTURES

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Abstract

Seismic vulnerability assessment is a comprehensive process that involves evaluating the susceptibility of structures to potential damage or failure during seismic events. This assessment is crucial for understanding and mitigating the impact of earthquakes on structures. Still, it is necessary to emphasize that vulnerability assessment is not a singular procedure: it varies based on the scale of analysis and the specific goals of the assessment. Conducting such assessments requires significant technical expertise as well as human and financial resources, which are often limited. These challenges are particularly evident in historic urban areas due to the unique characteristics of historical buildings, including complex materials, construction techniques, and the difficulty of quantifying their cultural value and significance.

Methods for assessing structural vulnerability can be categorized into empirical, analytical, expert-based, or hybrid approaches.

The paper discusses the existing vulnerability assessment methods presented by various authors, emphasizing the advantages and disadvantages of each and examining their practical applications.

Keywords: vulnerability, review, empirical methods, analytical methods, expert-based methods, hybrid methods

1. Introduction

Earthquakes, though relatively rare, can exert some of the most significant horizontal forces on structures, causing not only physical destruction but also loss of life and other far-reaching consequences. Seismic risk is assessed using three key factors: seismic hazard, exposure, and vulnerability. Seismic hazard refers to the probability of earthquakes causing destructive effects in a specific area, often expressed as the likelihood of exceeding certain ground motion parameters (PGA) within a defined period and depicted on seismic hazard maps. Exposure represents the concentration of human activity and assets, such as buildings and infrastructure, in the observed area. Vulnerability reflects the susceptibility of structures to the damage caused by seismic forces, enabling the estimation of the probability of specific damage levels during an earthquake. Understanding these three factors allows for better evaluation and mitigation of seismic risk, contributing to safer design and disaster preparedness [1]. The seismic hazard is given by natural geological processes; therefore, it is beyond the human control. Exposure theoretically can be altered, by measures such as relocating the population or organizing new settlements through urban planning. Nevertheless, such an approach is difficult to implement in practice. On the other hand, the vulnerability of the building stock is the easiest factor to influence. Still, in order to decrease it, in case of existing structures, firstly, it needs to be assessed. There are several distinct approaches to assessing seismic vulnerability, commonly grouped into empirical, analytical, expert-based, and hybrid methods.

The authors are conducting a large-scale vulnerability assessment of Lower Town, historical centre of Zagreb. The preliminary assessment based on existing methods has been performed and the scatter between expected and observed damage was noted [2]. The modified method applicable for Croatia is being developed, hence the state-of-the-art review is essential to navigate the numerous existing approaches.

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2. Empirical methods

Empirical methods are often associated with the statistical analysis of post-earthquake inspection data, usually represented in the form of damage probability matrices (DPM). A damage probability matrix, introduced by Whitman et al. in 1973 [3], systematically represents the likelihood of a structure reaching a specific damage level (damage state) under varying seismic intensities. These methods can be further divided into two categories: Rapid Visual Screening (RVS) assessment methods and vulnerability index methods [4]. RVS methods are the simplest vulnerability assessment techniques, based on visual surveys that don't involve detailed calculations or investigations. These methods rely solely on external building observations, ignoring interior factors. RVS is particularly useful for quick, preliminary vulnerability assessments in cases of urgency or limited data access, helping prioritize actions. It is also suitable for large building stocks since it can be completed in under 30 minutes. The RVS method defines 17 building types and assigns each a "Basic Structural Hazard" (BSH) score, which reflects the probability of structural collapse. The BSH score is then adjusted by score modifiers (SM) based on factors such as the number of stories, building height, plan and vertical irregularities, soil type, and construction age. RVS methods have been developed and implemented in countries such as United States, Canada, Japan, New Zealand, Turkey and Greece.

The Vulnerability Index Method (VIM) is widely used for seismic vulnerability assessment due to its straightforward approach, involving seismic hazard analysis, vulnerability analysis, and damage evaluation via the damage probability matrix. In recent decades, the GNDT (National Group of Defense from Earthquakes) approach in Italy has been vocal in developing vulnerability index methods. These methods are classified into two levels: "GNDT level I" and "GNDT level II." "GNDT level I" classifies buildings into typological classes and defines vulnerability classes A, B, and C, while "GNDT level II" integrates the work of Benedetti et al [5]. The method, based on extensive damage data and building stock information, defines parameters that influence seismic response and applies a weighting process, considering the importance of each parameter through expert judgment (Table 1).

Table 1 Vulnerability index method [5]

Parameter	Class				Weight factor
	A	B	C	D	
1. Connection of walls	0	5	20	45	1,00
2. Type of walls	0	5	25	45	0,25
3. Soil condition	0	5	25	45	0,75
4. Total shear resistance of walls	0	5	25	45	1,50
5. Plan regularity	0	5	25	45	0,50
6. Elevation regularity	0	5	25	45	(*)
7. Horizontal diaphragms	0	5	15	45	(*)
8. Roof	0	15	25	45	(*)
9. Details	0	0	25	45	0,25
10. General maintenance conditions	0	5	25	45	1,00

A modified version of the VIM developed by Benedetti and Petrini [5], was proposed by Formisano et al [6]. This method introduces five additional parameters with corresponding weight factors to capture the aggregate effect more accurately (Table 2). These parameters were selected based on a thorough review of previous studies and expert judgment. To justify the weight factors, several pushover analyses were conducted for each new parameter. Diverse boundary conditions among adjacent structural units were simulated, and the pushover analyses were performed using the 3MURI software, which employs the Frame by Macro-Elements (FME) method. The structural response was evaluated using the mechanical vulnerability index (IM) in both isolated and aggregate conditions, calculated as the ratio of demand to capacity in terms of displacement. This modified VIM is commonly used in both research and practice to assess the collective impact of various factors on structural vulnerability.

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Table 2 Parameters that capture the aggregate effect [6]

Parameter	Class				Weight factor
	A	B	C	D	
1. Presence of adjacent buildings with different height	-20	0	15	45	1,00
2. Position of the building in the aggregate	-45	-25	-15	0	1,50
3. Presence and number of staggered floors	0	15	25	45	0,50
4. Effect of either structural or typological heterogeneity among adjacent structural unit	-15	-10	0	45	1,20
5. Percentage difference of opening areas among adjacent facade	-20	0	25	45	1,00

The applicability of empirical methods is often constrained to specific regions. For instance, the VIM method was applied to the case study from Croatian building stock [7], [8] revealing significant discrepancies between the expected [2] and actual damage outcomes [9], [10].

Figure 1 Preliminary assessemnt in Zagreb; case studies [2]

A similar approach for considering the aggregate effect was proposed by Ferreira et al. [11]. The authors identified key factors in generating the aggregate effect, including height irregularities, misalignments of floors and/or openings, the quality of masonry, location, soil conditions, and the plan geometry.

In 1999, the European Union supported the RISK-UE project, aiming to develop a comprehensive seismic risk assessment methodology for European countries [4]. This initiative arose from the lack of a unified system across Europe. As part of the Risk-UE project, two models were proposed: a macroseismic model, intended to be used with macroseismic intensity hazard maps, and a mechanical-based model, designed for when the hazard is represented by peak ground accelerations and spectral values [12]. The macroseismic model introduced the VIM as an effective tool for vulnerability assessment, which was implemented in seven European cities. The VIM classifies buildings (including masonry, reinforced concrete, steel, and wooden structures) into six vulnerability classes (A to F). Each class is assigned a vulnerability index, which is then adjusted by a Behaviour Modifier Factor / Response Modification Factor, based on expert judgment, and a Regional Vulnerability Factor, derived from both historical data and expert judgment. Additionally, the approach categorizes damage into five grades, from slight damage to complete collapse, using the EMS-98 scale (D1 to D5).

However, it is important to note that producing an overall seismic risk assessment may not always be feasible due to the unique characteristics of different building stocks. For example, in one study [13], the authors compared the seismic vulnerability models for masonry and reinforced concrete structures

DOI: https://doi.org/10.5592/CO/3CroCEE.2025.4

from the Risk-UE project with experimental dynamic properties of buildings in France. They observed significant discrepancies between the proposed vulnerability curves and the experimental data. The authors recommended deriving curves for typological classes based on the number of stories, as they concluded that the elastic period (or frequency) is a function of building height and/or number of stories [13].

3. Analytical methods

Unlike empirical methods, which rely on observations, analytical methods depend on numerical models and simulations to assess the physical vulnerability of structures to seismic forces. Recently, advancements in structural modelling tools have broadened the scope of analytical approaches, allowing for the creation of vulnerability and fragility curves without relying on data from previous seismic events. Analytical methods can generally be categorized into detailed and simplified approaches. Detailed methods involve complex numerical simulations, including static or dynamic nonlinear analyses. However, due to the significant effort involved, simplified analytical methods have emerged as a more practical alternative. These simplified methods can be further divided into three subgroups: collapse mechanism-based (CMB) methods, capacity spectrum-based (CSB) methods, and fully displacement-based (FDB) methods.

CMB methods focus on predefined collapse mechanisms, such as in-plane and out-of-plane failures, and calculate corresponding collapse multipliers. The critical collapse mechanism is determined by identifying the lowest collapse multiplier, derived from the strength ratio of the structural walls' shear or flexural properties. This is calculated using the principle of virtual work, aligned with the static theorem of limit analysis. An example of this approach is discussed by the authors in [14], who suggested an automated procedure to evaluate local collapse mechanisms in masonry aggregates. In contrast, CSB methods derive the capacity curve through nonlinear analysis, which is then compared to the seismic demand. FDB methods, similar to CSB, also compare displacement capacities to seismic demands, but with the added complexity of accounting for changes in stiffness as a result of structural deformation and variations in period values [14].

Numerical modelling and seismic response simulations are crucial for analytical methods. Numerical modelling strategies fall into four categories: block-based models, continuum models, microelement models and geometry-based models. Each has unique features suited to specific applications:

1. **Block-Based Models**: These represent masonry as individual elements (blocks) bonded by mortar, reflecting its heterogeneity. Blocks can be modelled as rigid or deformable, with interactions defined by methods such as interface elements, contact-based, textured continuum, limit analysis, or extended finite element (FE) approaches. While highly detailed, they are computationally intensive and time-consuming.
2. **Continuum Models**: These treat masonry as a homogeneous, continuous material, omitting individual block and mortar distinctions. They are faster to compute since mesh size doesn't depend on masonry details but require complex constitutive laws to accurately represent the material.
3. **Macroelements Models**: These divide the structure into large-scale components, like piers and spandrels, based on geometry. They focus on in-plane behaviour and typically ignore out-of-plane failure mechanisms.
4. **Geometry-Based Models**: These represent structures as rigid bodies, emphasizing equilibrium and collapse mechanisms using static or kinematic theorems.

The research [15] by Tomić et al. confirms the impact of numerical modelling to the results. The study included conducting a shake table test with a case study consisting out of two masonry structural units. Afterwards, the input data had been provided to other researchers and engineers from practice in order to perform seismic analysis. A significant scatter was recorded among the output data and shake table test results.

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The process of deriving fragility and vulnerability curves through analytical methods is computationally intensive and time-consuming. These methods also face challenges due to the many uncertainties involved throughout the modelling process. Despite these difficulties, analytically derived curves have proven useful, especially when empirical data from past seismic events is unavailable. One such analytical method, META-FORMA [16], is an automated procedure for seismic performance assessment of masonry aggregates. It utilizes mechanical and geometrical parameters of structural units in a masonry aggregate as inputs to a vulnerability algorithm. Using MATLAB, the procedure interacts directly with structural analysis software (POR2000) to generate and analyse numerous numerical models, producing bilinear capacity curves and capacity/demand ratios. This method was successfully applied in a pilot study in the historical centre of Foggia, Italy. Its key advantage lies in its ability to quickly and simply estimate the seismic behaviour of masonry aggregates with minimal input data. A similar study conducted in the Azores on traditional stone masonry aggregates [16] focused on the overall seismic response of buildings, considering the interactions with adjacent buildings of varying heights. The global response was determined using nonlinear static analyses, emphasizing the importance of modelling the structure and adjacent buildings accurately to assess expected damage.

FaMIVE (Failure Mechanism Identification and Vulnerability Evaluation) method [17] is an analytical comprehensive method designed specifically for unreinforced masonry (URM) buildings. The method identifies failure mechanisms within masonry structures, focusing on in-plane, out-of-plane, and combined failure mechanisms (13 in total), and calculates collapse load factors for each façade, considering masonry properties and connections between structural elements. This analysis generates capacity curves and identifies the most probable failure mechanism. FaMIVE's versatility allows it to be used to generate vulnerability functions for various masonry structures globally.

4. Expert-based and hybrid methods

Expert-based methods involve conducting vulnerability assessments grounded in the knowledge and experience of specialists. Hybrid methods, on the other hand, represent a combination of these expert-based approaches with other methodologies. A notable example of such a hybrid approach is demonstrated in the work of Kappos et al., where damage probability matrices were developed to enhance risk assessment [18].

One comprehensive hybrid methodology is the HAZUS framework, which addresses natural hazards such as earthquakes, floods, and hurricanes [18]. This method integrates empirical data, analytical techniques, and expert knowledge. The HAZUS framework is organized into six interdependent modules, designed to support detailed and flexible loss estimation studies. Depending on the user's needs and the intended application, this modular structure allows for adjustments in the level of detail and precision [18]. A key feature of the HAZUS methodology is its classification system for buildings. Structures are categorized based on their use or occupancy to estimate economic losses and by their structural characteristics to predict damage. The method distinguishes 28 occupancy categories and 36 building typologies, classifying structures by factors such as structural type, material, height, and period.

5. Discussion and conclusion

The paper provides a brief state-of-the-art review and highlights aspects that require special attention when conducting vulnerability assessment. Seismic vulnerability assessment methods vary in approach and complexity, catering to different objectives and data availability. Empirical methods rely on observed damage patterns and statistical relationships to estimate vulnerability. The methods analyse historical earthquake data and are efficient for large-scale assessments but lack accuracy for individual buildings. Analytical methods, on the other hand, use structural modelling to simulate how buildings respond to seismic forces. While these methods provide more accurate results, they require extensive data and computational

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resources. Expert-based methods leverage specialists' judgment to assess vulnerability qualitatively, making them valuable for limited data scenarios or complex structures. These methods are particularly useful when data is limited or when dealing with complex structures that don't fit standard models. Hybrid methods combine empirical, analytical, and/or expert-based approaches, merging the strengths of each to offer a more comprehensive assessment. By using empirical data to validate analytical models and integrating expert insights, hybrid methods improve both the accuracy and practical applicability of seismic vulnerability evaluations. These methods can also be categorized as direct or indirect, depending on the steps involved in estimating earthquake damage. Direct methods establish a direct relationship between damage levels and earthquake intensity, while indirect methods include an additional step, typically involving the definition of a vulnerability index. Tools like the Analytic Hierarchy Process (AHP) and Geographic Information Systems (GIS) further support modern assessments.

Table 3 Comparison between vulnerability assessment methods

Methods	Empirical	Analytical	Expert - based	Hybrid
Strengths	Provides practical insights from past experiences	Systematic, repeatable, and data-driven	Useful when data is scarce, incorporates experience	Balances real-world data with theoretical analysis
Limitations	Limited to a certain area (also geological properties)	Requires time and computational efforts	Subjective and prone to biases	High data and resource requirements
Required data	Historical damage records, case studies	Physical properties, probability models	Expert knowledge and qualitative data	Combination of past data and theoretical models
Application scale	Local, urban, regional, national	Individual buildings, local	Local, urban	Local, urban, regional
Accuracy	Depends on data availability and relevance	High in controlled environments, but may not fully capture real-world complexity	Varies based on expert experience and knowledge	Generally more accurate than individual methods

Finally, seismic vulnerability assessments vary in methodology based on their specific aims and scale. The scale of assessment influences data collection, precision, and mitigation strategies At the individual building level, detailed surveys and numerical modelling provide precise assessments. At local and urban scales, methods focus on collective vulnerabilities, integrating empirical data, geospatial tools, and probabilistic models for broader insights. Regional and national assessments rely on simplified models and statistical analyses to identify large-scale trends. Given resource constraints, simpler methods are often used for large-scale evaluations while balancing accuracy and variability in building types. To conclude, method selection depends on the assessment's goals, with validation through post-earthquake data remaining essential.

Acknowledgements

This research is funded by the Croatian Science Foundation, grant number UIP-2019-04-3749 (ARES project—assessment and rehabilitation of existing structures—development of contemporary methods for masonry and timber structures), project leader: Mislav Stepinac.

DOI: https://doi.org/10.5592/CO/3CroCEE.2025.4

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