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Review article

State of the art of simplified analytical methods for seismic vulnerability assessment of unreinforced masonry buildings

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ABSTRACT

Cities in the developing world are facing outstanding economic and human losses caused by natural hazards such as earthquakes, and the amount of losses is affected by the quality of preventive measures and emergency management. For this reason, seismic vulnerability assessment is considered a crucial part of a strategy for seismic risk mitigation and for improving the resiliency of cities. Due to the high number of building archetypes for the seismic vulnerability assessment at a large scale, fast, simplified methods have been proposed that can facilitate the assessment procedure with low computational effort. Simplified methods can be categorized into three groups: analytical, empirical, and hybrid methods. In this study, simplified analytical methods for the seismic vulnerability assessment of unreinforced masonry (URM) buildings were reviewed, starting with their classification into three main groups: collapse mechanism-based, capacity spectrum-based, and fully displacement-based methods. Finally, attention was given to the corresponding software packages that were developed to facilitate the assessment procedure.

1. Introduction

In the past few decades, natural catastrophes, including earthquakes, have led to a dramatic increase in human and economic losses. A loss model for earthquake risk is required to predict the economic impact of future risks as well as to define risk mitigation plans by national authorities [1,2]. Seismic vulnerability assessment, which describes the susceptibility of a structure to damage due to ground shaking, is a pivotal part of a loss model [3,4]. Masonry buildings can be considered as the oldest construction type and represent a large part of the building portfolio in high seismicity zones. Fig. 1 presents a hazard map of the high seismicity zones in Europe and the Middle East based on the peak ground acceleration (PGA) of the area. Fig. 2 illustrates the ratio of the number of unreinforced masonry (URM) buildings compared to other types of structural systems in European countries, as well as the number of all buildings in each country [5]. URM is considered as a prevalent structural system in high seismicity zones, i.e., Italy, Greece, Bulgaria, Turkey, as depicted in Fig. 2, and Iran based on [6].

Fig. 3 (a) shows a hazard map of South America, and as illustrated in Fig. 3 (b), the prevalent construction type is URM. Fig. 3 (b) also shows the distribution of URM buildings, the number of all buildings (in millions), and the replacement cost for each country. The replacement cost is the value of replacing a constructed building based on the latest seismic code in a country [8].

URM buildings are characterized by a high seismic vulnerability; in fact, both the mortar and the masonry unit are known to be "quasi-brittle materials" whose mechanical performance could be deteriorated under seismic loadings. Due to the absence of a robust connection between structural components and insufficient stiffness of horizontal floors, URM buildings are highly susceptible to lateral cyclic loads that involve the out-of-plane bending behavior of walls and combined in-plane and out-of-plane collapse mechanisms [10–12].

Fig. 4 shows a seismic risk map of two susceptible zones where URMs are prevalent construction buildings. The reported average annual loss (AAL) in some parts of the high seismicity zones with high PGA is more than 5,000 USD per m^2, representing a severe economic loss for governments [13].

Based on the statistics from several earthquakes (1886–2003) in the United States, 20% of 4,457 URM buildings were either partially damaged or completely collapsed, and the reason for collapse for 83% of the damaged buildings was the brickwork fell [15]. As shown in Fig. 5, due to the vulnerability of this structural system, the construction of the

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new buildings made of URM is not permitted in some states of the United States [15].

In order to decrease human and economic losses, seismic vulnerability assessment of URM buildings is needed by national authorities at different scales. Different historical URM structures with complex architecture need to be preserved, as do existing vernacular URM buildings. In recent decades the resiliency of structures and infrastructures has attracted wide attention, and in order to facilitate a resiliency framework, a robust vulnerability assessment methodology is required to be applied at a large scale [16]. The methods should be user-friendly due to the high number of archetypes as well as be fast in computation [16,17]. Therefore, as illustrated in Fig. 6, the scale of vulnerability assessment procedures can be classified into three groups ranging from building scale to large scale [18].

Different seismic vulnerability assessment methods have been proposed in the literature and can be divided into three main groups: (1) empirical methods (EM), (2) analytical methods, and (3) hybrid methods (HM) (see Fig. 7). The most common methods for the seismic vulnerability assessment of building typologies at different scales aim to define a damage probability matrix [19] or fragility curves [20].

EMs are based on visual inspection of buildings in the post-emergency phase and damage data obtained from observed past earthquakes [21–25]. They refer to typological building classes or vulnerability indexes and can be correlated with construction techniques, types of materials, and different building features [26–31]. A limitation of these methods is their validity that can be limited to specific geographical and seismic regions [32].

Analytical methods require detailed vulnerability assessment algorithms to consider the physical and mechanical properties of buildings that can be calibrated to various characteristics of building stocks and hazards [33]. However, deriving analytical vulnerability curves is time-consuming and needs high computational effort. Consequently, basic users cannot easily develop curves for different areas or countries with diverse construction characteristics [3].

HMs are a combination of EMs and analytical methods whereby post-earthquake loss data is combined with results from analytical methods of a building typology [34,35]. Visual inspection data reduces computational efforts of analytical methods. Furthermore, HMs and EMs are utilized for calibrating the analytical methods [3].

Analytical methods can be divided into two sub-groups: detailed analytical methods (DAMs) and simplified analytical methods (SAMs). DAMs for the seismic vulnerability assessment of URM buildings comprise a sophisticated, detailed numerical simulation by conducting nonlinear analyses [36]. Different methods have been presented for nonlinear analysis of URM buildings in order to show their actual behavior when subjected to seismic loads. Nonlinear static (pushover) analysis (NSA) is the most popular method, where the lateral static load is applied to the model and is increased until a displacement target is reached [37]. Incremental dynamic analysis (IDA) is the most advanced type of detailed analysis, in which accelerograms are applied to the building model, and their intensity increased until the collapse occurs [10,38].

In order to reduce time consumption and computational effort, different simplified analytical methods (SAMs) for the seismic vulnerability assessment of URM buildings have been developed. Collapse mechanism-based (CMB) methods are based on the kinematic chain in order to derive the collapse multipliers for different probable collapse mechanisms of URM buildings subjected to a given intensity of a seismic record. Capacity curves are the result of the NSA. In capacity spectrum-based (CSB) methods, a predetermined capacity curve is computed for each building typology. The capacity curve is then intersected with the seismic demand to derive the performance points in different damage thresholds. In fully displacement-based (FDB) methods, an equivalent single-degree-of-freedom (ESDOF) model of a building is derived, and the displacement capacity for each damage threshold is compared to the displacement demand in each corresponding period of vibration in order to derive the possibility of crossing the damage thresholds [3,17,32].

When dealing with a single-building assessment, uncertainties are mainly due to the lack of expert knowledge of the structural features, which can be reduced by an on-site survey [39]. However, when dealing with vulnerability assessment at a large scale using the SAMs, a broad range of variables and a great deal of uncertainty are involved in both the modeling process and parameters [40,41]. Generally, uncertainty on capacity, demand, and damage thresholds are the sources that are

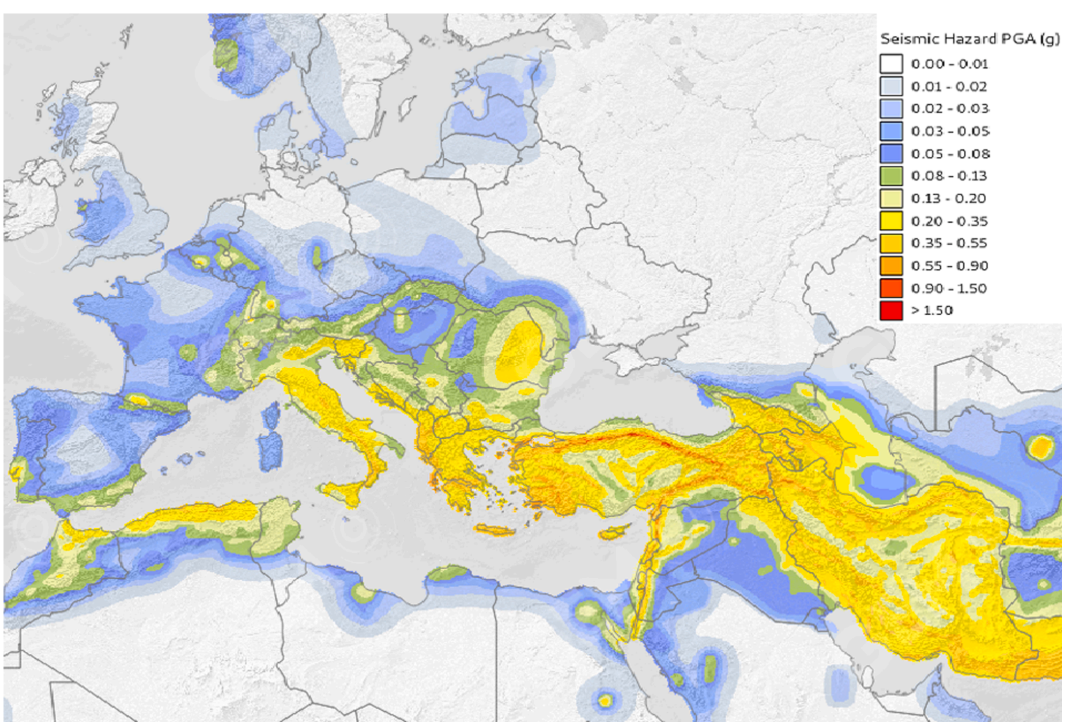


Fig. 1. Hazard map of the European and Middle-Eastern countries, based on PGA [7].

identified by most of the available seismic vulnerability assessment methods [42].

Fig. 8 presents a schematic overview of the scale of assessment and the complexity level of the analysis methodologies. As shown, the complexity and time consumption level increase from the green area to the red area, where the highest level is related to the IDA of detailed nonlinear models of all the buildings at a large scale, which is uncommon nowadays. Moreover, EMs requiring the lowest computational effort are not suitable for the seismic vulnerability assessment of single-building but only for the building stock scale and large scale. The yellow area shows the methods that nowadays are most commonly applied to a specific case study scale.

The aim of this paper is to provide a state-of-the-art review of the developments of the SAMs, which are categorized and illustrated in a black box in Fig. 8. The complexity and corresponding computational efforts of each method are investigated by emphasizing their mechanics basis, drawbacks, and advantages. Note that the main focus of this paper is on unreinforced brick masonry buildings; however, case studies about stone and adobe masonry have been addressed to present the operational scope of each method. Moreover, particular attention is given to different software packages that were developed to facilitate the application of the SAMs for the seismic vulnerability assessment of URM buildings by investigating their strengths and weaknesses.

2. Collapse mechanism-based methods

The main concept of CMB methods is to assess the vulnerability of URM buildings by defining predefined collapse mechanisms or decomposing them into rigid macroblocks. In CMB methods, first, collapse multipliers are computed, and the minimum value is defined. Then, the corresponding collapse mechanism is considered as the most critical mechanism.

VULNUS is one of the CMB methods proposed by Bernardini et al. [43] based on in-plane and out-of-plane collapse mechanisms of URM buildings. In this method, the collapse multipliers are derived from the ratio of shear strength and flexural of walls for in-plane and out-of-plane collapse mechanisms of URM walls by applying the virtual work principle according to the static theorem of limit analysis [44]. A comparative seismic assessment has been done for URM building aggregates within the historical center of Arsita damaged by the L'Aquila earthquake (2009, April 6th) in Italy [45]. A macroseismic EM was utilized to derive the vulnerability indexes and the corresponding fragility curves. Furthermore, the VULNUS method was used to derive the fragility curves. Within the VULNUS method, the terms I_1 and I_2 take into account the probable in-plane and out-of-plane mechanisms. Moreover, DAM was done by means of an equivalent frame method embedded in 3Muri software [46]. Detailed three-dimensional (3D) models were provided, NSA was done, which is described in detail in [47], and by means of the CSB method, the corresponding fragility curves have been derived. This study shows that the fragility curves derived from the VULNUS method are placed in the middle range between the upper limit (conservative) DAM and the lower limit ones derived from the EM of the fragility domain [45].

Performance-based assessment and the seismic risk mitigation of cultural heritage assets were incorporated into the Italian guidelines (PCM) [48] outlined by the Italian building code [49]. For this purpose, a CMB method was added to and recommended by the Italian guidelines [36]. Some of the predefined collapse mechanisms in the PCM are illustrated in Fig. 9 [50,51].

Using SAMs associated with an ESDOF modeling of buildings is not reliable enough for global evaluation of URM cultural heritage sites with complex architecture. Therefore, investigating the local mechanisms using the CMB methods is needed to be done. Not only the predefined collapse mechanisms but also the lack of connections with the orthogonal walls, infinite compression resistance (rigid blocks), and zero tensile resistance strength are the simplified hypotheses considered in this

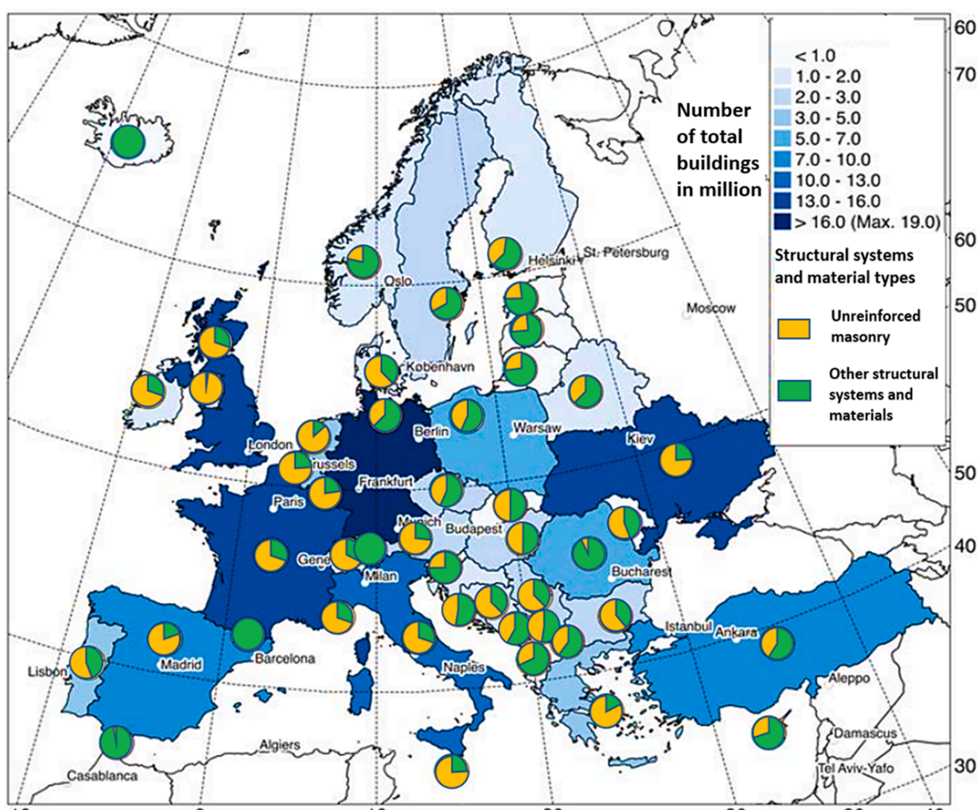


Fig. 2. Exposure of the distribution of URM buildings and the number of all buildings (in millions) in European countries, adapted from [5].

type of analysis [52].

A damage assessment was done for the churches after the L'Aquila earthquake (2009) using the PCM method, see [53]. Totally 28 predefined collapse mechanisms were considered to cover all the collapses that may occur for the macroelements of the churches such as façade, nave, transept, triumphal arch, dome, apse, roof covering, chapel, and bell tower. According to this study, seismic behavior evaluation of the URM churches using the PCM method has been proven as a rapid and reliable method. Moreover, it was concluded that the substitution of timber roofs with reinforced concrete (RC) slabs cause an increase in mass and stiffness, which produced negative effects on the behavior of the churches that should be avoided as a restoration method in the future [53].

The mentioned CMB methods were then developed by importing the actual 3D geometry by considering the irregularities of the masonry towers to assess the susceptibility of them subjected to different distributions of horizontal loads [54]. Five predefined collapse mechanisms, including rocking, Heyman's diagonal cracking, and base shear sliding, were hypothesized for the kinematic limit analysis (KLA) of the towers in [55], and an optimization algorithm was embedded to minimize the failure multiplier of each mechanism.

The 3D KLA-based method was applied to two URM towers, and the results were compared with the results of nonlinear static and dynamic analyses of the detailed finite element models (FEMs). The method is believed to be considered a reliable tool for most cases; however, increasing the number of failure mechanisms such as rocking on the upper corners or the collapse of the belfry can increase the method's accuracy [54].

The possibility of importing the actual 3D geometry of the case study and applying different distributions of horizontal loads are considered as the two main advantages of the 3D KLA-based method for the URM towers that can be expanded to be used for the assessment of URM building aggregates. Nevertheless, computing the collapse multipliers for the predefined collapse mechanisms is a limitation in the proposed KLA methods. To address this limitation and decrease the level of uncertainties related to modeling and capacity, mentioned CMB methods were developed by modeling the structures with rigid macroblocks considering indefinite collapse mechanisms [36].

The application of the CMB method for predicting the masonry domes' failure behavior subjected to static horizontal loads has been investigated in [56]. The dome was modeled by means of a few rigid non-uniform rational basis spline (NURBS) elements, with the hinges at the element edges forming the failure mechanism. KLA was performed on a NURBS model and compared with the results of the NSA of a detailed FEM, and the ultimate load factors were the same, which shows the reliability of this method [56].

The NURBS-based KLA method was then developed [57] to find the minimum collapse multiplier of historical URM building aggregates. In order to estimate the minimum collapse multiplier and investigate the exact position of the fracture lines, a genetic algorithm-based mesh adaptation was applied to a 3D model of the whole aggregate, modeled with NURBS surfaces.

Seismic vulnerability of one of the URM aggregates, named I1 Torrione in Arista, Italy, was assessed using different types of modeling approaches [58]. Four different structural units were chosen from the whole building and modeled using the NURBS-based KLA method to identify the local failure mechanism multipliers. Moreover, both local and global mechanisms were evaluated by performing the NSA on an equivalent frame model of the building in the 3Muri software package [46,59]. Furthermore, the FEM of the aggregate has been provided, and the results from the NSA were compared to other methods' results.

The evaluation of a safety factor, which is the ratio between the spectral acceleration and the maximum acceptable value has been performed for all the methods. Comparing the safety factors obtained from the analyses results of the four mentioned methods illustrates that the analyses using the equivalent frame method in 3Muri software have the

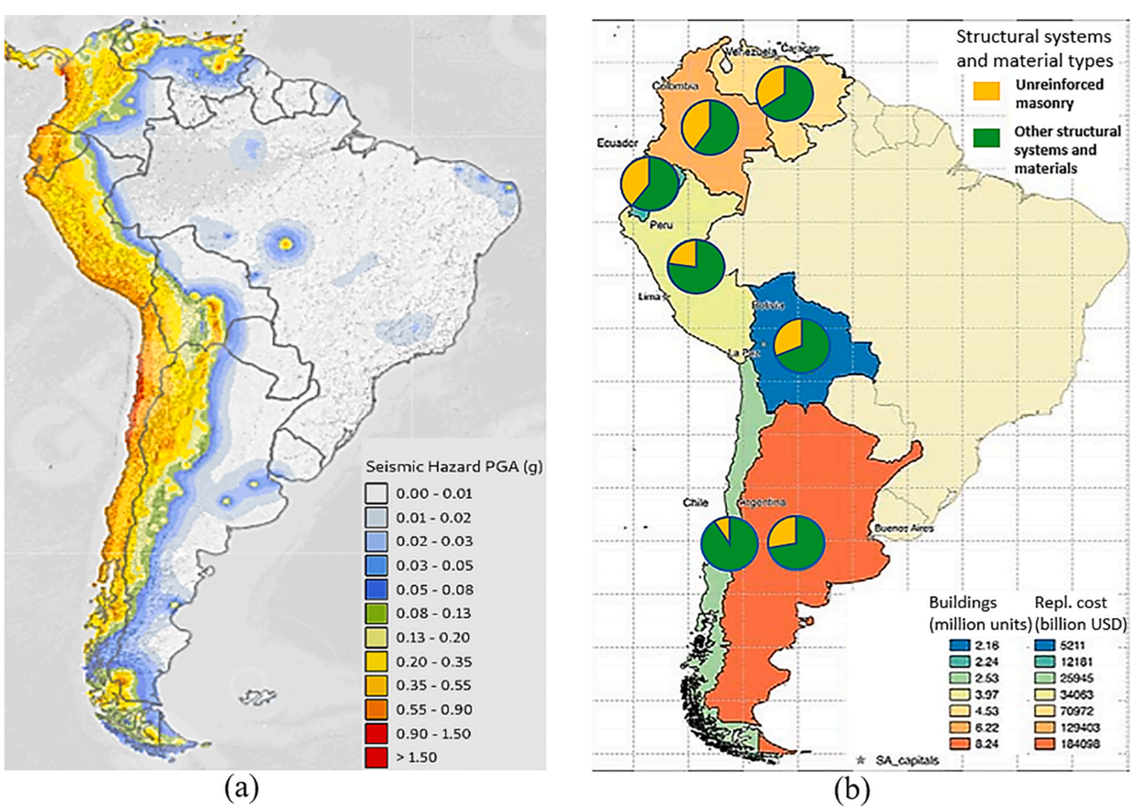


Fig. 3. Hazard map of South America based on PGA [7] (a), and distribution of structural systems, number of all buildings (in millions), and replacement costs (in billion USD), adapted from [9] (b).

largest safety factor value for the building since out-of-plane failure modes have been neglected. NSA was done on the FEM of the building with more computational effort compared to the analysis in the 3Muri software package. However, the safety factor derived from the finite element analysis is lower than the result from 3Muri since the out-of-plane collapse mechanism has been considered. Local mechanism analysis using the 3Muri software package is in the third rank with a fast and enough accurate methodology. Nevertheless, predefined collapse mechanisms have been considered. Finally, the lowest safety factor refers to the local analyses using the NURBS-based KLA method with low computational efforts and automatic mesh adaptation [58].

For the seismic vulnerability assessment of heritage URM buildings with complex architecture, that the global behavior of the structure is not guaranteed, CMB methods are recommended as a very fast and accurate enough method. Since in-situ destructive tests are rarely allowed for the heritage buildings and corresponding high level of uncertainties about structural details, several models need to be analyzed. Therefore, the FEM approach with high computational effort is not recommended.

Detail about each reviewed CMB method is summarized in Table 1, which can facilitate comparing the methods. Moreover, relevant references for some applications have been provided. Although it can be seen that for some of CMB methods (i.e., VULNUS, PCM) the in-plane collapse mechanisms have also been evaluated, the main focus of the CMB methods is to evaluate the local mechanisms occurring due to the presence of flexible diaphragms with a poor connection to the URM walls which can be observed in old buildings.

2.1. Software packages

c-Sisma is a KLA-based software designed to investigate the predetermined collapse mechanism multipliers in which the material properties, wall geometry, and seismic loads are considered as inputs for the software; where the multipliers for each collapse are the outputs [67]. c-Sisma is based on predetermined collapse mechanisms specially designed for typical residential URM buildings, but some software packages were developed to investigate all collapse mechanisms and different types of structures, including arches, domes, and vaults. Brickwork is one of the CMB method software packages that includes

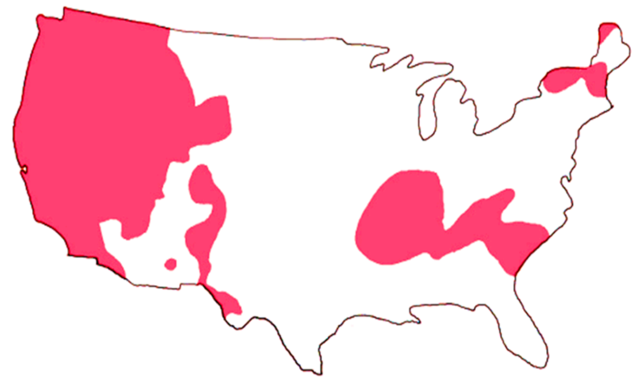
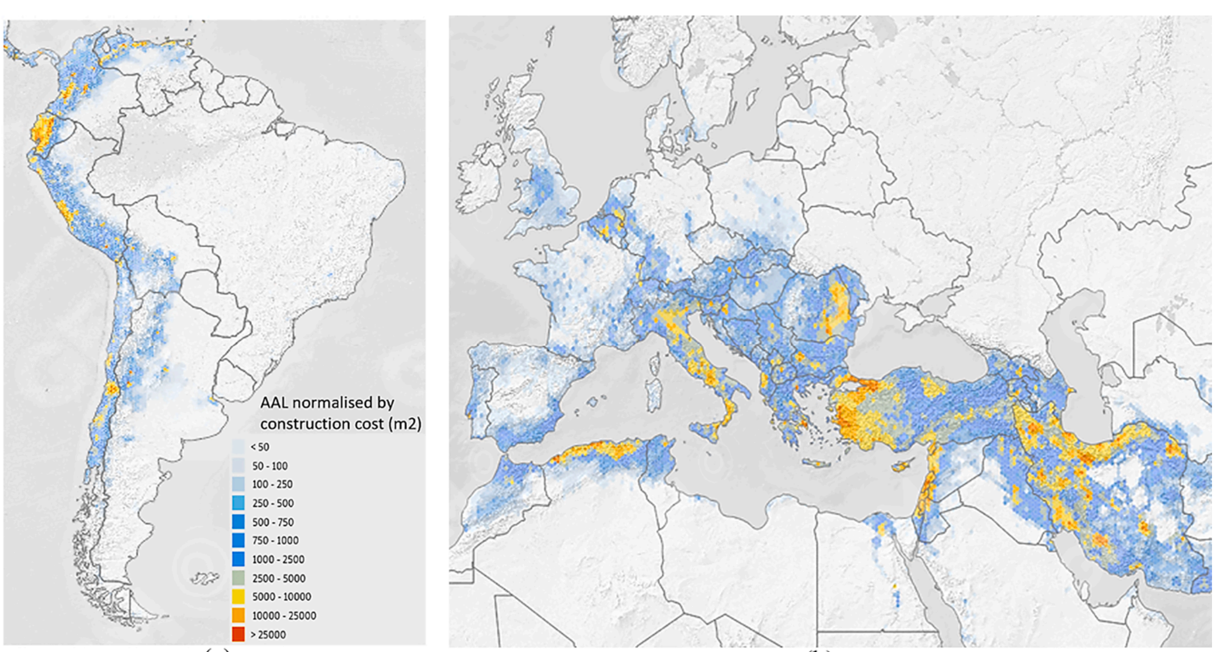


Fig. 5. Approximate mapping of the zones in which current seismic codes do not allow the construction of URM buildings in the United States [15].

these developments in two-dimensional (2D) environments [68] to be developed and verified by comparing to finite element analysis results [69].

A macro-block software [70] was developed for the assessment of out-of-plane behavior of URM walls based on the details elaborated by Lagomarsino [71] in the context of the PERPETUATE project [72] aimed for the performance-based assessment of cultural heritage assets. The interface software is developed and added to the 3Muri software as a module for local collapse mechanism assessment of URM walls based on the predefined collapse mechanisms that are prescribed by the user. A 3D model of a building can be defined, and the collapse mechanisms and the constraints for each component should be specified, and the corresponding collapse multipliers will be calculated based on the kinematic analysis rules [59].

UB-ALMANAC uses an adaptive NURBS-based KLA approach, which is another fast and user-friendly software for upper-bound limit analysis of URM buildings [56,73]. The UB-ALMANAC is used for the seismic vulnerability assessment of churches by 3D modeling of the structure with rigid macro blocks joined by elastoplastic interfaces to derive the collapse multiplier and the most probable collapse mechanism. It can consider the directions of seismic loads, different mesh sizes and types,



(a) (b)

Fig. 4. Seismic risk map including exposure of AAL in South America (a), and European countries and Middle Eastern seismic susceptible zones (b) based on PGA as shown in Figs. 1 and 3(a) [14].

Fig. 6. Different scales of the seismic vulnerability assessment procedures.

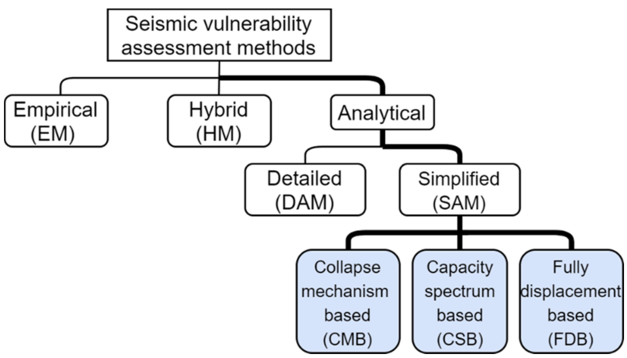


Fig. 7. Seismic vulnerability assessment methods classification. The methods in the blue boxes have been elaborated in this study. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

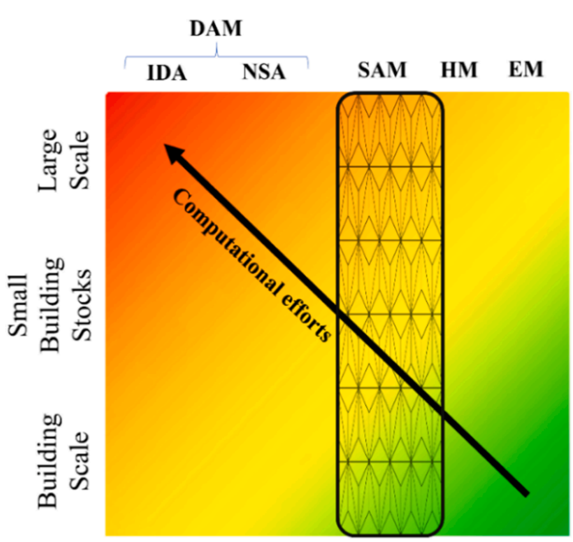


Fig. 8. Schematic overview of different methods as a function of the scales of assessment and corresponding computational efforts.

and interconnection of the walls [74]. LiABlock_3D is a MATLAB-based tool with a graphical user interface into which computer aided design (CAD) files can be easily imported, allowing high flexibility in structural configuration [75].

3. Capacity spectrum-based methods

The Capacity Spectrum-Based (CSB) Method has spread considerably in the last three decades because it can be considered a valid alternative to nonlinear time-history analysis. It was introduced in ATC-40 [76] and implemented in HAZUS methodology for earthquake loss estimation [77]. Other alternative versions of CSB methods are available in FEMA 273 [78] and the N2 method [79,80] that is introduced nowadays in Eurocode 8-part 3 [81]. The N2 method was formulated in the acceleration – displacement format by Fajfar [80], although the original idea of this method dates back to the mid-1980s [82].

The general procedure of the CSB methods is synthesized in Fig. 10. The capacity curve of a building is derived from NSA, and then it is transformed from a multi-degree-of-freedom (MDOF) system into an ESDOF system, as shown in Fig. 10 step 1. It is recommended that capacity curves for URM buildings be fitted via a bilinear elastoplastic capacity curve as illustrated in step 2 [38]. The idealized capacity curve will be intersected with seismic demand in order to compute the performance point of the structure. The seismic demand can be evaluated by selecting the ground motion record and deriving the inelastic response spectrum that allows identifying the performance point that defines the inelastic displacement demand for a specific ground motion, as shown in Fig. 10 step 3. A set of ground motion records can be selected, and the procedure above described can be repeated for increasing ground motion intensities (e.g., Fig. 10 step 3a) up to all limit states are reached so that the earthquake demand parameters can be evaluated for each damage state and the fragility curves that represent the probability of occurrence of a specific damage state for a given seismic demand can be derived [38,72,80]. Alternatively, the smoothed elastic code-based spectrum can be used as shown in Fig. 10 step 3-b. However, the last alternative cannot reflect record-to-record variability; consequently, it is not recommended to develop fragility curves because it does not account for uncertainties due to ground motions.

Different simplified CSB methods have been proposed in literature in a way that the pushover curves are derived for a simplified model [83]. Among them, the failure mechanism identification and vulnerability evaluation (FaMIVE) method is one of the most noteworthy. It was first introduced as a CMB method by D'Ayala [84] to assess the vulnerability of historic URM buildings in town centers.

The collapse multipliers were calculated for probable collapse mechanisms by considering both in-plane and out-of-plane failures through an equivalent static procedure. Twelve probable mechanisms are identified, as shown in Fig. 11, and the most probable mechanism is associated with the lowest base shear capacity [84].

The specific feature of FaMIVE is strictly related to how the data collection is organized by on-site inspection, concentrating on those parameters that can directly qualify the seismic performance of URM buildings and can mostly be surveyed from a rapid visual screening.

The buildings are classified with approximately the same typological layouts, masonry fabrics, and quality of materials. Data collection by performing the on-site inspection is the preliminary step of the FaMIVE method to collect specific information for each building, such as height, length, the thickness of each accessible façade, number of stories,

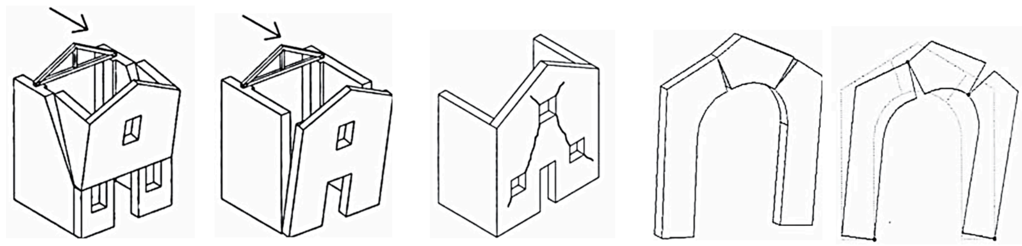


Fig. 9. Different predefined collapse mechanisms in PCM [48].

Table 1
Details about each CMB method and the relevant references for the applications.

Method	Collapse mechanism	Data collection	Output	Brief description	References
VULNUS	1 predefined in-plane and 1 predefined out-of-plane collapse mechanisms	On-site survey	Collapse mechanisms' acceleration and the most probable collapse mechanisms	Computation of collapse multipliers applicable for URM small building stocks.	[44,45,60–63]
PCM	28 predefined in-plane and out-of-plane collapse mechanisms	On-site survey	Collapse mechanisms' acceleration and the most probable collapse mechanisms	Computation of collapse multipliers applicable for URM churches or towers (at building scale).	[51–53,64–66]
3D KLA-based (Towers)	5 predefined collapse mechanisms	On-site and 3D geometrical survey	Collapse mechanisms' acceleration and the most probable collapse mechanisms	Deriving the most probable collapse mechanism of a 3D model applicable for URM towers (at building scale) using optimization algorithms.	[54]
NURBS-based KLA	Indefinite local mechanisms	On-site and 3D geometrical survey	Collapse acceleration and possible fracture lines	Deriving the most probable collapse mechanism of URM buildings' structural components modeled with rigid NURBS elements (at building scale).	[56–58]

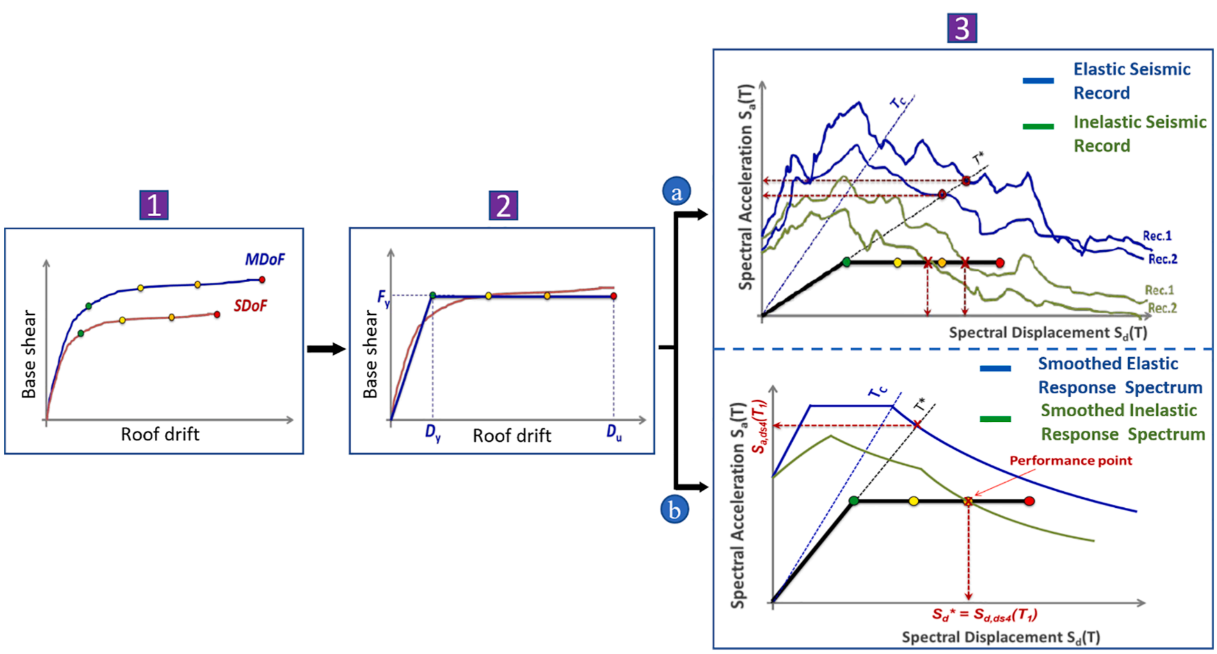


Fig. 10. General procedure of CSB methods, after [38].

strengthening devices, etc. It is possible to input on-site survey data electronically, which is automatically stored in the database sheet to calculate the failure load factors.

Based on the information collected, the ultimate load factor of each external wall for each collapse mechanism is calculated. The collapse mechanism for a given façade depends on the type of connections to the rest of the structure, mainly due to the type of horizontal structures, because if the floor is not rigid in its plane, like vaults or wood floors, it affects the redistribution due to a seismic action that depends from the connections with internal walls and position of the timber beams or vaults. The lower mechanism in terms of collapse acceleration is the most probable one, selected to calculate the fragility curves [85] that can directly be obtained from the collapse accelerations, as illustrated in Fig. 12 with the first alternative.

Then this method was extended from a purely CMB method into a CSB method [32,86]. For each failure mechanism, a specific capacity curve is defined with the aim to define fragility curves. The reliability of the procedure is strictly connected to the idealized capacity curves of the ESDOF model and to the selected limit states. In particular, the authors use the NSA by means of the N2 method, as proposed in Eurocode part 3 [81], where the performance point is evaluated using a degrading pushover curve. This procedure is illustrated in a simplified way in Fig. 12, alternative 2. The capacity curve can be computed and intersected to the acceleration-displacement seismic demand spectra to

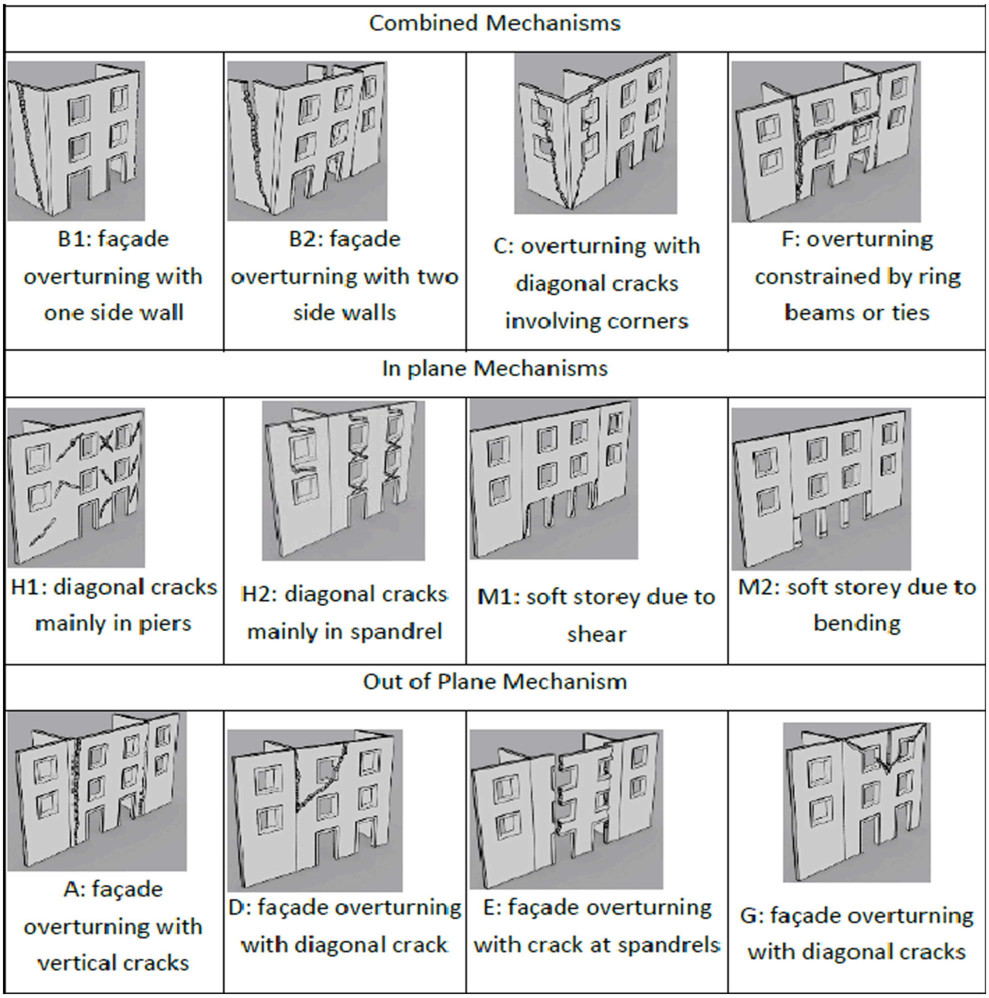


Fig. 11. Collapse mechanisms in FaMIVE methodology [84].

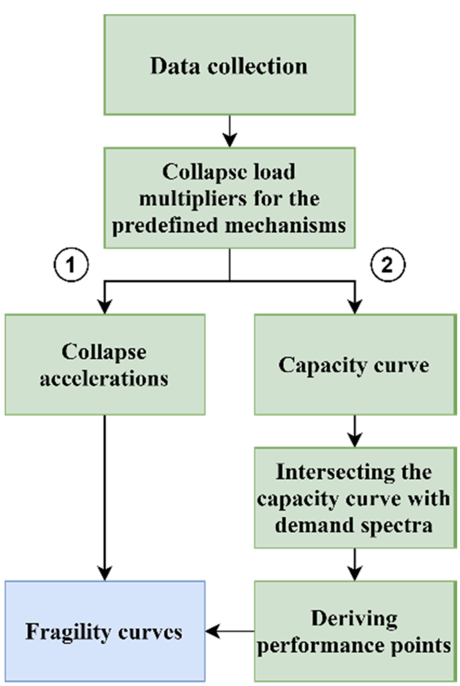


Fig. 12. Flowchart of FaMIVE methodology for deriving fragility curves [38].

define performance points. Fragility curves are then developed from performance points for each building typology [87–89].

Four limit states have been considered for the FaMIVE method based on the pushover curve. Damage limitation (DL) corresponds to the ultimate elastic capacity, significant damage (SD) corresponds to the first peak capacity point, near collapse (NC) limit state corresponds to the maximum displacement without shear resistance degradation, and the collapse (C) limit state corresponds to the ultimate capacity point. The corresponding computed inter-story drifts ratio (IDR) of the mentioned limit states have been summarized in Table 2.

The FaMIVE procedure allows the retention of a high level of detail of the geometry and kinematics of the problem. Simultaneously, since it computes only the ultimate condition, it does not require the computation or time demands of a typical NSA [38].

Uncertainties related to damage thresholds, capacity, and demand have been considered in the FaMIVE method, which are effective on fragility curves. Furthermore, epistemic uncertainties concerning the reliability of input data from the on-site survey form have been contemplated [32].

The FaMIVE method has been utilized for the seismic vulnerability assessment at a large scale for Casbah of Algiers in Algeria [90] in the context of Perpetuate project [72]. First of all, significant building typologies have been identified evaluating the seismic performance of these selected buildings in terms of lateral capacity and collapse mechanisms. Different intervention recommendations were proposed to enhance the Algerian construction quality [90].

The European Commission launched the RISK-UE project [91] in seismic risk analysis, concentrating on the distinctive features of European cities regarding modern and historical buildings [92]. For this purpose, Lagomarsino [93] presented a mechanical procedure for the seismic risk assessment of both URM and RC frames, which was proposed in the framework of the RISK-UE project.

This method uses simplified bilinear capacity spectra, derived depending on the building typology's geometrical and characteristics, including the number of floors, material properties, drift capacity, and timespan of construction. Moreover, for URM buildings designed without any seismic criteria, a prevailing collapse mode is defined based on the method presented in [94]. The uniform collapse mode or the soft-story collapse mode due to rocking or shear failures has been considered, while the out-of-plane mechanisms have been neglected.

By assuming a bilinear representation, the capacity curve is identified in terms of yield spectral displacement and acceleration (d_y and a_y respectively) and ultimate spectral displacement and acceleration (d_u and a_u, respectively) points. In the further hypothesis to neglect hardening behavior, capacity curves can be defined by three parameters: the yield acceleration a_y, the fundamental period of the building T, and the structural ductility capacity μ.

The authors proposed a set of European building typology classifications for masonry and RC buildings. In particular, for URM buildings, they introduced six typologies for URM and one typology for reinforced masonry buildings. For each of them, different types of horizontal structures have been considered: wood slabs, masonry vaults, composite steel and masonry slabs, and reinforced concrete. Moreover, three possible intervals have been considered for the number of stories: low-rise with 1–2 stories, mid-rise with 3–5 stories, high- rise with more than six stories. For each building typology, the parameters that define the capacity curves are presented in a table, with the great advantage that the user can directly consider the capacity curve proposed by the authors, and it is not required to model the building. In this approach, once capacity spectra are derived for the building classes, the next step is to use the CSB method. The performance point of each building class is obtained by intersecting the capacity spectrum with the inelastic acceleration-displacement response spectrum, which is produced by using codified spectral shapes calibrated to the PGA obtained from the hazard analysis. Four damage states were considered in order to investigate the level of damage, which can be derived from predefined equations based on the yielding d_y and ultimate d_u displacements [93].

In the context of the RISK-UE project, the seismic risk evaluation of about 60,000 residential buildings in the city of Barcelona in Spain was done using the simplified mechanical method [93]. In particular, six-building classes were considered to develop two damage scenarios realized for deterministic and probabilistic seismic hazard. It was concluded that URM buildings show higher vulnerability compared to RC building typologies. Moreover, maximum damage values were expected for high-rise URM buildings located on soft soils [95].

Pagnini et al.[96] proposed an analytical method to assess the vulnerability of masonry buildings based on a few mechanical and geometrical characteristics of the buildings that are used to derive the bilinear capacity spectrum of the ESDOF model [96,97]. The capacity spectrum method has been applied considering the formulation of the N2 procedure. This method focuses on the effects of the uncertainties related to the mechanical properties and limit states, showing the role of each uncertainty on the results. In order to derive the capacity curve, a URM building of height H is schematized with a stick model based on [98] where each floor is represented with a lamped mass. The capacity curves have been extracted considering the effects of uncertainties related to the specific weight of masonry, shear modulus, shear strength, resistant wall areas, floor loading, inter-story height, and the non-uniform response of the masonry panels [97]. In particular, the authors use Taylor's series around the mean value to account for the uncertainties of the parameter. The propagation of uncertainties has been studied considering the influence of each parameter at a time on the capacity curve. The results show that the most relevant parameters are the resistant wall area in the considered direction and the shear strength. Four random limit states that lie on the mean point have been analyzed as a function of buildings parameters. Then, the fragility curves are derived, including all uncertainties' effects.

The damage thresholds' types and the corresponding values for each presented CSB method have been shown in Table 2 and compared with the limit states proposed in HAZUS [99], Eurocode 8-part 3 [81], and FEMA 356 [100]. The damage thresholds can significantly influence the fragility curve shape, but the values proposed by various authors and codes can be very different, as shown in Table 2, where the damage thresholds are defined as a function of the inter-story drift ratio IDR, the roof displacement, and the spectral displacement.

CSB methods cannot precisely reflect certain dynamic phenomena such as near-field velocity pulses that can considerably influence the structural responses [101]. Table 3 summarizes each aforementioned CSB methods' main feature comparing the type of data collection required to define the input data, the collapse mechanisms considered in the methods, and the relevant references for some case studies. Note that the input demand data is considered nonlinear response spectra with different return periods. The data collection type can be done by performing on-site surveys to record the structural and geometrical detail of the building samples or exposure database provided by the authorities to define the general data about the building typologies at a large scale. All methods are proposed for URM buildings with different horizontal structures, including the flexible, the semi-rigid, and the rigid floor. Among the analyzed methods, only the FaMIVE procedure [32] considers the out-of-plane collapse mechanism and the collapse multipliers that can be evaluated from the structural analysis. The simplified mechanical method (RISK-UE project) [93] considers only the global mechanism but propose a set of European typological masonry structures and, for each of them, the authors evaluated the capacity curves parameters that are presented in a table so that the user doesn't need to define a structural model for a large scale vulnerability assessment. The uncertainties have been considered both in FaMIVE and Pagini et al. [96] methods; in particular, the last method proposed a sensitivity analysis of the results as a function of each parameter. All the CSB methods are suitable to consider the record-to-record variability in terms of using seismic records as demands.

3.1. Software packages

The main concept of these methods is the intersection of the capacity curves and the seismic demands to derive the performance points in different damage thresholds [16,108]. Some software packages are related to a specific region, and the capacity curves are related to a typical structural system and configuration in that specific area. Moreover, their exposure can be at urban or multi-level scale, meaning country scale. Geographical Information Systems (GISs) and remote sensing technologies have helped create comprehensive databases and systems for data exposure, analysis, and damage evaluation [109]. All the information about the CSB software packages can be found in Table 4, including relevant references for more information.

A comprehensive study was carried out in a World Bank's Disaster Risk Management Section report, evaluating software packages developed for quantifying risk from natural hazards, including earthquakes [124]. Table 5 summarizes the advantages and disadvantages of some of the well-known CSB methods software packages.

4. Fully displacement-based methods

The main concept of the FDB methods is based on comparing displacement capacities of the ESDOF model of a URM building at different damage thresholds with seismic demands at the corresponding vibration period values of the model, which can be derived from secant stiffness of the capacity curve at each threshold. Although the FDB methods have some common aspects with the CSB methods, their

Table 2
Damage thresholds definition with corresponding values of the codes and the mentioned CSB methods.

Method name	Method type	Damage threshold type	Limit states and their values			
HAZUS (pre-code)	Code	IDR (%)	Slight damage	Moderate damage	Extensive damage	Complete damage
			0.2	0.5	1.2	2.8
HAZUS (low-code)			0.3	0.6	1.5	3.5
Eurocode 8-Part 3	Code	Roof (top) displacement	Limited damage	Significant damage	Near collapse	
			Yielding point of the idealized bilinear capacity curve	75% of the top displacement capacity corresponding the total base shear	Corresponding displacement of 80% of peak base shear	
FEMA 356	Code	IDR (%)	Immediate occupancy	Life safety	Collapse prevention	
			0.3	0.6	1	
FaMIVE (in-plane)	CSB	IDR (%)	Damage limitation	Significant damage	Near collapse	collapse
			0.18–0.23	0.65–0.9	1.23–1.92	1–2.8
FaMIVE (out-of-plane)			0.33	0.88	2.3	4.8
Mechanical method (RISK-UE project)	CSB	Spectral top displacement	Slight damage	Moderate damage	Extensive damage	Complete damage
			0.7 d_y	d_y	$d_y + 0.25(d_u - d_y)$	d_u
Pagini et al.	CSB	Spectral top displacement	0.7 d_y	1.5 d_y	0. 5 $(d_u + d_y)$	d_u

Table 3
Details about each CSB method and the relevant references for the applications.

Method	Data collection	Collapse type	Output	Brief description	References
FaMIVE	On-site survey	In-plane and out-of-plane	Collapse acceleration, the most probable collapse mechanism capacity curve, performance point, fragility curve	Collapse multipliers have been calculated for nine predefined collapse mechanisms, and the most probable mechanism has been derived. Fragility curves can be derived directly from the collapse multipliers or using the CSB procedure.	[32,90,102–104]
Mechanical method (RISK-UE Project)	Exposure Database and on-site survey	In-plane	Capacity curve, performance points, fragility curve	Derivation of bilinear capacity curves for building typologies based on structural description and using CSB procedure to derive the performance points.	[1,95,105,106]
Pagini et al.	Exposure Database and on-site survey	In-plane	Capacity curve, performance points, fragility curve	Derivation of bilinear capacity curves considering uncertainty effects based on the structural description and using CSB procedure to derive the performance point.	[96,107]

Table 4
CSB Loss estimation software packages.

Name	Modifiability[1]	GIS-based	Region	Exposure	Owner	Programming language	References
HAZUS-MH	CS	Yes	North America	Multi	FEMA, NIBS/USGS	VB6, C++, ArcGIS	[110,111]
CAPRA	OS	No	Central America	Multi	EIRD/World Bank	Visual Basic.NET	[112]
ELER	OS	No	Europe	Urban	NERIES/JRA-3, NORSAR, Imperial	Matlab	[113]
EQRM	OS/CS	No	Australia	Urban	Geoscience Australia	Matlab/Python	[114]
EQSIM	CS	No	Europe	Urban	CEDIM/KIT	C++, xmf	[115]
HAZ-Taiwan	CS	No	Asia	Multi	National Science Council/NCREE	Microsoft Visual C++ and MapInfo	[116]
LNECLOSS	CS	Yes	Europe	Urban	LNEC, Consortium	Fortran	[117]
Ergo (MAEviz/ mHARP)	OS	Yes	World	Urban	University of Illinois at Urbana Champaign	EclipseRichClient, Geotools	[118]
OpenQuake	OS	No	World	Multi	GEM	Python, Java	[119]
SAFER	OS	No	World	Urban	23 Worldwide Institutions/Multiple EU	Matlab, C++	[120]
SELENA	OS	Yes	World	Urban	NORSAR	Matlab, C++	[121]
OOFIMS	OS	No	World	Multi	SYNER-G EC FP7/Univ. of Rome 'Sapienza'	Matlab	[122]
HAZTURK	CS	Yes	Turkey	Urban	Istanbul Technical University	Java, GIS plug-in	[123]

1 CS: Closed Source, OS: Open Source.

procedure appears to be quite different because the main aim of the CSB method is to evaluate the performance point of the structure from the intersection between the capacity curve of the structure and the demand response spectra. In contrast, in FDB methods for each building class, the displacement capacities are compared with the displacement demand considering the changing of the building stiffness, and the result is the probability of occurrence that specific limit state.

The first developments of the FDB method for URM buildings can be found in Calvi study [125]. The method evaluates the seismic building response for each limit state by the displacement capacity and introduces a correction factor as a function of the dissipated energy. The elastic displacement response is then defined as demand, derived based

Table 5
Advantages and disadvantages of software packages of CSB methods, adapted from [124].

Name	Advantages	Disadvantages
HAZUS-MH	✓ A well-known software package with a detailed user and technical manual. ✓ A full decision module with benefit-cost ratio calculators and mitigation aspects. ✓ Many US building typologies have been included in the software.	× The software is only calibrated to be used for the United States building stocks. × The package cannot operate without (ArcGIS) software. × The software does not explicitly include uncertainty, and the variability of the results can be examined by performing sensitivity analyses. × Epistemic uncertainty is not considered.
CAPRA	✓ Hazard can be input from other programs as long as the file is in the right format (.ame, .txt, or .atn). ✓ A very good rerun capability. ✓ A user-friendly software and easy for basic users to understand the errors. ✓ Well-handled uncertainty consideration. ✓ Inbuilt extendable GIS useful for loss estimations.	× The fatality and economic functions lack a lot of diversity. × The damage distribution is not calculated directly and only a mean damage ratio is available. × No formal manual is provided. × Mix of Spanish and English software language makes the entire interface quite challenging to maneuver.
EQRM	✓ The software offers a large number of exposure options for hazard and risk. ✓ Event-based probabilistic seismic hazard risk assessment with this level of detail and analysis has been provided. ✓ Easy level of modifiability for the MATLAB based type of the software.	× The software is not integrated with GIS. × There is no graphical user interface.
Ergo (MAEviz/ mHARP)	✓ Completely open source with an inbuilt GIS platform. ✓ Scenario risk assessment and decision support are provided. ✓ User-friendly with a large array of infrastructure types for analysis.	× Currently calibrated only for deterministic analysis.
OpenQuake	✓ A well-prepared user manual. ✓ A wide range of hazard and risk analysis tools has been included. ✓ It currently offers the most in-depth probabilistic analysis of any of the reviewed software packages for earthquakes. ✓ Uncertainties related to the seismic hazard is considered.	× Looks only at residential buildings. × No graphical user interface yet.
SELENA	✓ User-friendly with an easy-to-use graphical user interface. ✓ All types of logic trees are allowed in order to consider the uncertainties and calculate the loss.	× Outputs are quite difficult to manipulate compared to other packages. × The high number of input text files makes it complicated to run without errors.

on the return period, seismicity of the location, and local soil conditions. For each building class, two probabilistic limit values are evaluated for the period of vibration and the displacement capacity defining a series of rectangular in the displacement spectrum in which the probability density function is defined (see Fig. 13). Each rectangular can be intersected by the input motion defined by a spectral curve, so that the probability of occurrence of each limit state can be evaluated. This probability of occurrence indicates the percentage of buildings that reach a specific limit state. If the displacement response spectrum crosses the rectangular region, it is possible to evaluate whether the demand is greater or less than the capacity. Alternatively, this probability can be interpreted as the percentage of buildings that attain that limit state. In particular, four limit states have been considered for structural damage; but the out-of-plane collapse mechanisms are not included.[126]. The results of the study show hard soil spectra produce more damage than soft soil spectra due to the shorter periods of vibration [125].

MeBaSe (mechanical based procedure for the seismic risk estimation of unreinforced masonry buildings) was developed by Restrepo et al. [127] as one of the FDB methods presented for RC and masonry buildings. As illustrated in Fig. 14, an ESDOF model of the building is computed with the equivalent mass (m_{eff}) and stiffness (K_{eff}) based on the model proposed in [98]. K_{eff} is calculated as the ratio of the yielding force of the system (F_y) and the effective displacement (Δ_{eff}) for a given displacement demand or limit state (Δ_{LS}), and the simplified bilinear capacity curve will be computed as illustrated in Fig. 14.

Four damage thresholds are considered in the MeBaSe, as illustrated in Fig. 15. No damage (limit state 1) or minor structural damage (limit state 2) corresponds to profile (a) in which the structural components have not reached the yield displacement Δ_y and the triangular shape is considered for low-rise URM buildings dominated by a shear failure mode. Profile (b) is the most probable damage failure for URM buildings. Profile (c) occurs at the top or intermediate stories, depending on the relative stiffness of the story. Profile (d) is related to the strength of substructures such as piers and spandrels. Three aforementioned profiles correspond to limit state 3, and collapse is defined as limit state 4.

The maximum displacement for a given limit state (Δ_{LS}) can be computed as the sum of the yield displacement (Δ_y) and the plastic displacement (Δ_p) [127,128]. Δ_{LS} for each limit state is computed using equation (1).

$$\Delta_{LS} = \kappa_1 h_T \delta_y + \kappa_2 (\delta_{LS} - \delta_y) h_{sp} \quad (1)$$

where $\kappa_1$and κ_2 show the mass distribution in the height of the building that can be obtained from [127] based on the number of stories, δ_y and δ_{LS}correspond to the yielding and the specific limit state drift, h_T and h_{sp}correspond to the total height and effective height of the piers going to the inelastic range. Note that the values for the drift damage thresholds (δ_y,δ_{LS}) can be selected from the experimental test results.

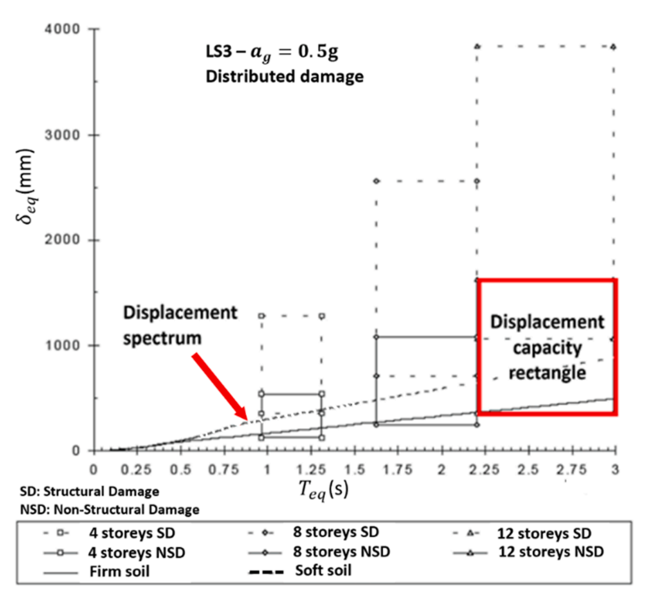


Fig. 13. Comparing displacement capacity rectangle and displacement spectrum-based on CALVI method, adapted from [125].

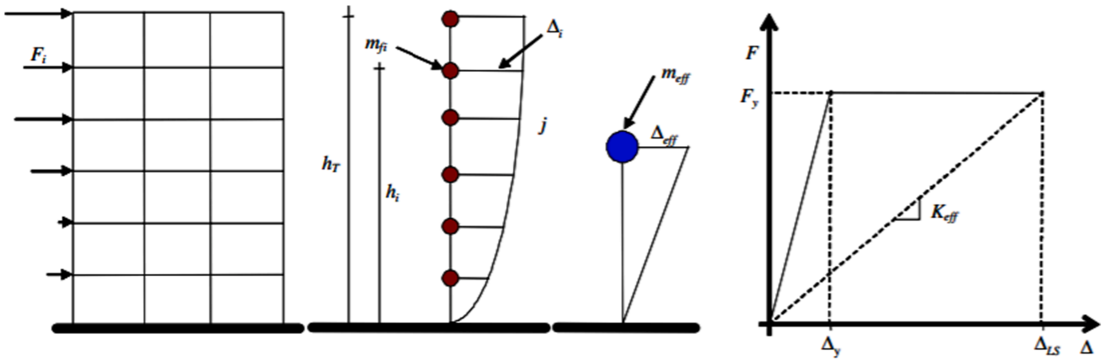


Fig. 14. Schematic view of the MDOF system versus ESDOF and the capacity curve.

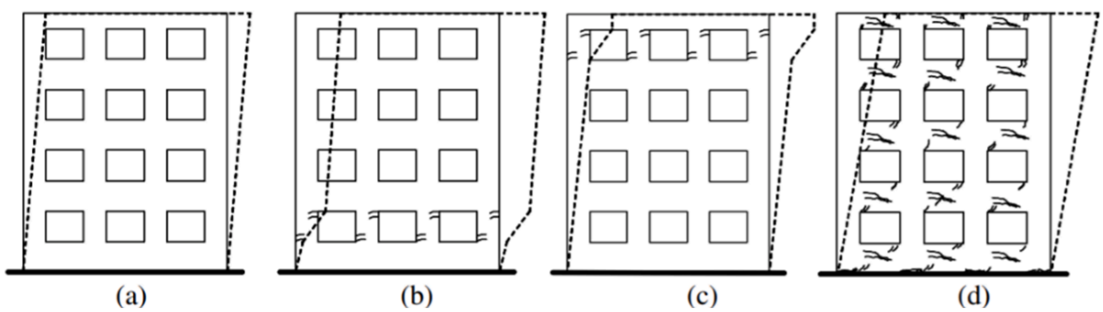


Fig. 15. Different damage thresholds based on the MeBaSe method [127].

The elastic displacement response spectrum, properly scaled for considering the effective damping of each damage threshold, will be considered as the seismic demand. The total probabilities of reaching or exceeding a damage threshold will be calculated for reporting the seismic vulnerability of the buildings.

One-way and two-way bending out-of-plane mechanisms and different levels of uncertainties have been considered in MeBaSe while they were not included in Calvi's method. Out-of-plane damage thresholds definitions of URM walls are based on [129], and one limit state has been considered for the out-of-plane collapse mechanism to define whether the structural component is collapsed or not. For this purpose, ultimate displacement considering the purely rocking behavior of the wall as a rigid body is defined and the collapse displacement is calculated as a fraction of the ultimate displacement based on the experimental tests' results [129]. However, in terms of demand for out-of-plane failure mode, seismic spectral demand for non-structural elements can be utilized.

The MeBaSe method was then developed for seismic fragility assessment of low-rise stone URM buildings in the old historic center of Quebec City, Canada [130]. Four drift thresholds for in-plane failure mechanism are considered and material properties are obtained from experimental tests of stone masonry walls to reduce the uncertainty level of the results. Note that out-of-plane failure mode is neglected in the case study by assuming a sufficient connection between the walls and the roof system [130].

The displacement-based earthquake loss assessment (DBELA) method is an FDB method that was originally developed for RC structures [131,132], but by considering the emerging concepts of performance-based engineering for URM buildings presented in [133], DBELA was then developed to be used for the assessment of URM buildings, as well [134].

The DBELA method [134] uses the basic concept of an ESDOF substitute model based on [98], with a bilinear capacity curve considering post-yield degradation behavior. A building will be converted into an ESDOF model with an equivalent mass and height. Furthermore, the ESDOF system tends to represent the actual behavior of a building in terms of its equivalent displacement and actual energy dissipation. A random population is derived using Monte Carlo simulation, and the displacement capacity of each building is then estimated at different damage thresholds considered for the global performance level of the buildings based on Equation (1). The displacement capacities are derived based on the simple mechanics of material principle for different inelastic deformation profiles [134]. The computed displacement capacity of the buildings will then be compared with the displacement demand of the expected ground motions on the site obtained in terms of 5% damped displacement response spectra, using site-specific empirical ground-motion prediction equation (GMPE) equation based on [135] at the corresponding fundamental vibration periods of different limit states.

The DBELA method was used to assess the seismic vulnerability of confined masonry buildings in Lima, Peru, as a reliable, fast, and computationally efficient FDB method [136]. Moreover, the DBELA method was used to derive the direct socio-economic losses of URM buildings in the city of Mansehra, Pakistan [134]. Three earthquake scenarios have been considered, and direct economic losses, homeless people in the city, and human injuries or death were estimated. These data can be very important for the government authorities to be aware of the expected seismic hazards to plan for the loss reduction. The formulation of DBELA is limited only to the URM building with rigid RC diaphragms that can be improved to consider other types of roof systems, i.e., wooden floors.

SP-BELA is another FDB method especially proposed for RC structures and then developed for the seismic vulnerability assessment of URM buildings [137]. A pushover curve is defined in SP-BELA so that the vibration period and the collapse mechanism are not predefined and can be derived from the NSA. However, since the NSA of the building aggregates is time-consuming, collapse multipliers and collapse mechanisms and the corresponding capacity curves can be computed based on simplified mechanical equations.

The probabilistic framework of the first-order reliability method has been used in MeBaSe to calculate the variability in the capacity and the time-invariant reliability formula to define the probability of collapse.

Nevertheless, the probabilistic structure in SP-BELA and DBELA for convolving variability in the displacement capacity and demand to calculate the probability of exceedance of limit states is based on the definition of the capacity curve for each building generated in a random dataset through Monte Carlo simulation with less computational efforts compared to the MeBaSe method. Simplified bilinear pushover curves are derived for the buildings of a dataset based on the mechanical-based equations with a reasonable level of computational effort.

The displacement demand is then calculated for each building and directly compared with the corresponding displacement capacity to determine whether a given limit state is exceeded or reached. The procedure to calculate the probability of exceedance of each limit state condition is graphically illustrated in Fig. 16. For each building in a sample, the equivalent period of vibration (T), the displacement capacity (Δ_{cap}), and the corresponding simplified capacity curve are computed. The demand in SP-BELA is modeled using spectral displacement ordinates (S_d). As shown in Fig. 16 (a), box 1, the displacement capacity of each limit state is converted into a spectral system and plotted for comparison with the spectral demand displacement. The dissipation of energy is taken into account through a coefficient η related to the damage and the ductility, based on [137]. The coefficient η, which is lower than 1, has been applied by multiplying the spectral demand ordinate or dividing the displacement capacity as illustrated in Fig. 16 (a), box 2.

As illustrated in Fig. 16 (a), if the point (spectral displacement capacity) is above the spectral curve, the capacity (Δ_{cap}) is higher than the demand (Δ_{dem}), and the corresponding building passes the damage threshold. When the point is below the spectrum, demand is higher than capacity, and the building does not attain the corresponding damage threshold and thus belongs to the higher limit state condition. As shown in Fig. 16 (b), the exceedance probability of the building aggregates has been carried out by repeating the comparison procedure and dividing the number of points below the spectral curve by the total population. Note that updating the building sample size during the methodology procedure is an advantage of SP-BELA compared to other mentioned FDB methods that reduces the computational efforts.

Capacity displacement damage thresholds are derived using Equation (1) for the in-plane failure mode. Three different drift limits have been identified for brick masonry with a low percentage of voids (LPV), a high percentage of voids (HPV), and for natural stones that just correspond to the third limit state as presented in Table 6. The methodology utilized for deriving the unique out-of-plane damage threshold and the corresponding capacity curve, which was embedded in the MeBaSe method, has been used in the SP-BELA method. Uncertainties related to damage thresholds, capacity, and demand have been inspected in SP-BELA by considering variability in drift limit states, buildings' characteristics, and spectral displacement demand, respectively [137].

SP-BELA is then calibrated for the large-scale vulnerability assessment by comparison with the results from the damage probability matrices elaborated in [93] and then by comparison with real damage data in terms of a damage scenario [138].

Recently SP-BELA is used to derive the fragility functions for adobe masonry buildings in Peruvian Andes, Peru, where 67% of rural buildings are adobe masonry. The simplified bilinear and trilinear capacity curves were derived by combining the in-plane and out-of-plane behavior of the buildings [139]. For this purpose, in-plane capacity was calculated based on the SP-BELA method, and out-of-plane behavior was represented by a lateral force-displacement curve based on [129]. First, displacement capacity for the out-of-plane actions was compared with the spectral displacement demands derived from a group of seismic records. If the building passed the acceptability check and did not satisfy the failure criteria, in-plane capacities for each damage threshold were compared with the demands. Finally, the combined fragility curves, considering both failure mechanisms, were derived [139].

The limit state values in CSB methods and the corresponding software packages are derived based on the mechanical equations related to the stiffness, mass, and height of the building after deriving the pushover curves; however, in well-known FDB methods (MeBaSe, DBELA, and SP-BELA) inter-story drift limit states should be defined performing experimental tests on the structural components to reduce the uncertainties. Afterward, the displacement capacities for each damage threshold can be defined using Equation (1). The inter-story drift limit states values utilized for the seismic vulnerability assessment of specific case studies with different construction material using mentioned FDB methods have been summarized in Table 6.

A simplified FDB loss assessment methodology for different building typologies, including URM buildings, was proposed by O'Reilly et al. [140] in the framework of the research consortium ReLUIS (Italian

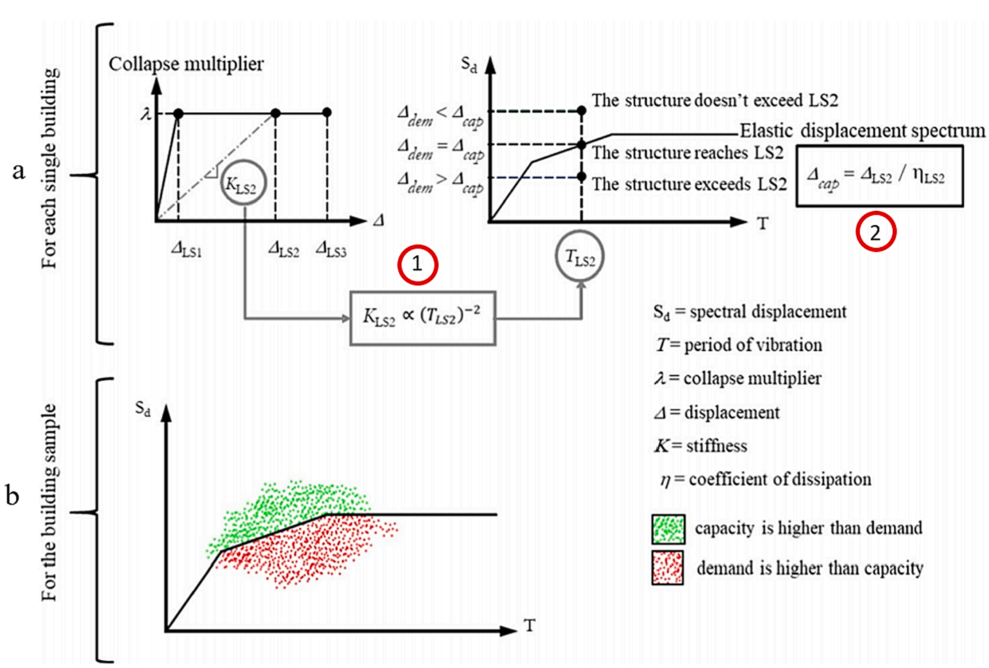


Fig. 16. Analytical methodology of SP-BELA, adapted from [138].

Table 6
Inter-storey drift limit states in percentage, utilized for the seismic vulnerability assessment of case studies using FDB methods.

Method name	Material type	Region	Limit states and their values in percentage (%)					References
Calvi	Brick masonry	Italy	Limit state 1 0.1	Limit state 2 0.3	Limit state 3 0.5			[125]
DBELA	Brick masonry	Northern Pakistan	0.08	0.15	0.35			[134]
SP-BELA	Adobe masonry	Peru (Peruvian Andes)	0.052	0.26	0.52			[139]
	Brick and stone masonry	Italy	Limit state 1 0.13	Limit state 2 0.34	Limit state 3 for LPV[1] (Brick) 0.72	Limit state 3 for HPV[2] (Brick) 0.45	Limit state 3 for Natural stone 0.61	[137]
MeBaSe	Stone masonry	Canada (Quebec)	Slight 0.13	Moderate 0.32	Extensive 0.68	Complete 1.03		[130]

1 low percentage of voids.
2 high percentage of voids.

acronym for University Laboratories Network of Seismic Engineering) in Italy, funded between 2014 and 2018. An FDB methodology for the seismic loss assessment of URM buildings, which needs nonlinear analysis of detailed numerical models of the buildings in the framework of the ReLUIS project was also developed, which lies outside the scope of this study [141]. Nevertheless, in another approach, a simplified loss assessment methodology was applied to a URM school in Italy using a simplified FDB method [140].

A bilinear capacity curve of the ESDOF model based on [142] was defined by a yielding base shear capacity depending mainly on input parameters such as geometric features, material properties, mode shapes, and expected failure mechanisms. The ultimate capacity was computed based on the main prevailing mode of failure. Subsequently, the displacement thresholds were determined for each limit state. The yield displacement is computed as a function of maximum base shear and the effective stiffness, and the second and the third damage thresholds are derived linearly with respect to the first limit state. The fourth failure mode corresponds to the combination between the critical failure mode and the adequate story drift proposed in [142]. The ultimate displacement is computed considering both mentioned failure modes. After characterizing the force-displacement relationship, fragility curves were computed using an analytical formulation [141].

The mean annual frequency of exceedance of each damage threshold was derived from the site hazard curve using the intensity computed from the FDB method, and expected annual loss can be estimated. Detail about the simplified loss assessment methodology lies outside the scope of this study described in [140,141].

The methodology proposed in [140] has been applied to a URM school to evaluate the annual expected loss value. The comparison between the results from this SAM with the results from NSA of the building modeled in the 3Muri software [46] shows a good correlation and, the methodology can be utilized for loss estimation of URM buildings with less computational efforts compared to time-demanding DAMs.

Although the CSB methods usually need less computational effort compared to the recent FDB methods and require fewer structural details, the FaMIVE method can be an exception as described in the text. Therefore, the CSB methods are usually considered efficient methods when details are not available, but in locations where a high level of details are available, the CSB methods can yield a higher level of uncertainties compared to the FDB methods [108,109]. Detail about each FDB method and relevant references for the case studies have been summarized in Table 7. One method for collecting data is the generation of a random population of buildings that should represent the whole building stock typology utilized in DBELA [134] and SP-BELA [137] methods. Note that FDB methods can be calibrated and utilized for the seismic vulnerability assessment of URM buildings with flexible, semi-rigid, and rigid floor systems; however, the connection of the walls to the floor plays a key role in investigating the out-of-plane collapse mechanisms. The out-of-plane collapse mechanisms, which can be critical for URM buildings, are considered in the MeBaSe [127] and SP-BELA methods and neglected in other FDB methods and can be neglected by assuming a robust connection between the floor and the URM walls.

Table 7
Details about each FDB method and the relevant references for the applications.

Method	Data collection	Collapse type	Input demand data	Applications	References
Calvi	Exposure database	In-plane	Design displacement spectra considering energy dissipation and damping effects	Computation of the probability of occurring a limit state by intersecting the capacity rectangles and the demand line.	[125,143]
MeBaSe	Exposure database	In-plane	Elastic Displacement spectrum considering damping effects	Computation of the limit states' capacity displacement and comparison of the values with the demand displacements at the limit state's corresponding vibration period of the structure.	[127,130]
		Out-of-plane	Acceleration demand for non-structural elements		
DBELA	Random population	In-plane	5% damped displacement spectra using site-specific GMPE	Derivation of the idealized bilinear capacity curve considering post-yield degradation, defining the limit states, and investigating the probability of reaching or exceeding each limit state to the demand displacements.	[134,136,144,145]
SP-BELA	Random population	In-plane	5% damped displacement spectra with definite PGA values	Computation of the displacement capacity, and the vibration period of the building at each limit state for in-plane and out-of-plane collapse mechanisms and investigating the probability of reaching or exceeding each limit state to the demand displacements.	[138,139,146,147]
		Out-of-plane	Acceleration demands for non-structural elements		
O'Reilly et al.	On-site survey	In-plane	Damped displacement spectra	Estimation of annual expected loss value by computing the mean annual frequency of exceedance of each damage threshold using FDB procedure.	[140]

4.1. Software packages

DBELA [134] and SP-BELA [137] are two software packages that used the FDB method. Each software program was developed by EUCENTRE in Pavia, Italy, with a different code-built structure that is applicable to the seismic vulnerability assessment of URM buildings at a large scale. SP-BELA can be connected to a user-friendly web-based GIS tool, thus allowing basic analysts to access the data on exposure, vulnerability, and hazard. The software highlights critical situations in terms of a seismic scenario by providing seismic risk maps. Moreover, near real-time damage scenario analysis is provided [138].

Although FDB software packages, compared to the well-known CSB software packages (i.e., HAZUS, ELER, SELENA), give less variability in results, they require a reasonable sample of building typology data. Therefore, in an area with low knowledge about the building samples, CSB software packages are recommended [108]. Furthermore, to evaluate the losses due to each earthquake scenario, two or more software packages should be used to reduce uncertainties and provide more robust data.

5. Conclusion

Different types of SAMs were reviewed for the seismic vulnerability assessment of URM buildings and were categorized into three groups: (1) CMB, (2) CSB, and (3) FDB by emphasizing their mechanics basis, pros, and cons. Different software packages for each method were presented and reviewed by explaining their limitations and advantages.

CMB methods were presented as fast and reliable tools to assess the final collapse loading. For the seismic vulnerability assessment of historical URM buildings with complex architecture, using only global mechanism analysis may not reflect the actual behavior of a building. Therefore, the CMB methods are recommended to derive the collapse loadings for different local mechanisms and define the critical collapse mechanism with the lowest collapse loading value. These methods are widely applied to the seismic vulnerability assessment at building scale as a fast tool, but due to the simplicity, they are also widespread in large scale use. Considering predefined collapse mechanisms may cause unrealistic results; therefore, modeling the buildings with rigid blocks has attracted wide attention to overcome this shortcoming. Recently in order to decrease the level of epistemic uncertainties and speed up the analysis procedure, importing 3D drawings is tried to be embedded into the CMB method software packages.

CSB methods using mechanical methods to derive the capacity curves and intersect the capacity curves with the demand spectra are widely used for the seismic vulnerability assessment of URM buildings. All the CSB methods and the software packages, except the FaMIVE method, neglect the out-of-plane behavior of URM walls, which can be critical collapse mechanisms in old URM buildings. Although the FaMIVE method needs a high level of detail and all sources of uncertainties are considered in the methodology, the main general feature of the CSB methods and software packages is their efficiency, which makes them suitable for the assessment at a large scale. A lower level of input data, simplicity of the procedure, less computational efforts, and a high number of software packages with user-friendly graphical user interfaces and well-prepared user manuals that can be linked to the GIS environment are the advantages of the CSB methods compared to other methods. These advantages make the CSB methods more efficient and suitable for the seismic vulnerability assessment at a large scale when detail input data is not provided for the location of a case study.

FDB methods investigate the probability of reaching or exceeding the limit state displacement values to the demand displacements at the corresponding secant stiffness of a building. The FDB methods and software packages usually need more detailed input data about the buildings and more computational efforts compared to the conventional CSB methods. Nevertheless, in locations that detail data about the building typologies is provided, the FDB methods can be more reliable with less level of uncertainty. Although the out-of-plane behavior of URM walls is usually neglected in the CSB methods, except for the FaMIVE method, this phenomenon is evaluated in the MeBaSe and SP-BELA methods.

All the methods for the seismic vulnerability assessment at a large scale should be verified based on the post-earthquake loss data from previous seismic events to find the most reliable method which can be applied in different areas, with different building typologies, as well as being fast and easy to use for the users. Although the mentioned software packages are used for the seismic vulnerability assessment of different cities and building stocks, it is necessary to use different well-known software packages in a specific area to reduce the uncertainty level and conclude robust results.

CRediT authorship contribution statement

Amirhosein Shabani: Conceptualization, Methodology, Investigation, Resources, Data curation, Writing - original draft, Visualization. **Mahdi Kioumarsi:** Conceptualization, Methodology, Writing - review & editing, Supervision, Project administration, Funding acquisition. **Maria Zucconi:** Conceptualization, Methodology, Resources, Writing - review & editing, Visualization, Supervision.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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