Fragility Curves for Italian Urm Buildings Based on a Hybrid Method

Antonio Sandoli (antonio.sandoli@unina.it)
University of Naples Federico II: Universita degli Studi di Napoli Federico II
Gian Piero Lignola
University of Naples Federico II: Universita degli Studi di Napoli Federico II
Bruno Calderoni
University of Naples Federico II: Universita degli Studi di Napoli Federico II
Andrea Prota
University of Naples Federico II: Universita degli Studi di Napoli Federico II

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Abstract

A hybrid seismic fragility model for territorial-scale seismic vulnerability assessment of masonry buildings is developed and presented in this paper. The method combines expert-judgment and mechanical approaches to derive typological fragility curves for Italian residential masonry building stock. The first classifies Italian masonry buildings in five different typological classes as function of age of construction, structural typology, and seismic behaviour and damaging of buildings observed following the most severe earthquakes occurred in Italy. The second, based on numerical analyses results conducted on building prototypes, provides all the parameters necessary for developing fragility functions.

Peak-Ground Acceleration (*PGA*) at Ultimate Limit State attainable by each building's class has been chosen as an Intensity Measure (*IM*) to represent fragility curves: three types of curve have been developed, each referred to mean, maximum and minim value of *PGA*s defined for each buildings class.

To represent the expected damage scenario for increasing earthquake intensities, a correlation between *PGA*s and Mercalli-Cancani-Sieber (*MCS*) macroseismic intensity scale has been used and the corresponding fragility curves developed.

Results show that the proposed building's classes are representative of the Italian masonry building stock and that fragility curves are effective for predicting both seismic vulnerability and expected damage scenarios for seismic-prone areas. Finally, the fragility curves have been compared with empirical curves obtained through a macroseismic approach on Italian masonry buildings available in literature, underlining the differences between the methods.

1. Introduction

Due to its particular position between the African and Euro-Asiatic plate, Italy is recognized as one of the countries of the Mediterranean basin affected by high-frequent and high-intensity earthquakes. Starting from the 1908 Messina and Reggio Calabria's earthquake (with M_w=7.1 and 100,000 victims estimated)) up to the last 2016-17 Central Italy seismic sequences (M_w=6.5), severe seismic events interested Italy during the 20th century. A brief reconnaissance of the most important earthquakes occurred in Italy in the last century is reported in Fig. 1, represented in terms of magnitude (M_w) and Mercalli-Cancani-Sieber (*MCS*) macroseismic scale by means of histograms. Consequences of these earthquakes were often devastating not only for the reconstruction costs (about of 180 billion euros in the last fifty years) but also for the casualties (more than 100,000 estimated in the last century) (DPC-2018).

Territorial-level seismic vulnerability assessment represents a fundamental tool to plan economical and human resources for mitigating the National seismic risk, especially in those countries exposed to a high seismic hazard. With the aim of this, different methods based on empirical, mechanical (or analytical), expert-judgment and hybrid approaches to assess seismic vulnerability and predict damage scenarios have been developed over the years by researchers (Calvi et al. 2006). Each method provides a classification of masonry buildings and defines the relative fragility curves for large-scale seismic assessment. In the case of empirical methods, either buildings' classification and fragility curves come from the statistical elaboration of data on damaged buildings collected in post-earthquake surveys. The main advantage is that, when well interpreted, real observed data is a realistic source of information and takes into account of building stock features and of ground motion effect. On the other side, disadvantages related to the heterogeneity of data of post-earthquake surveys and the unavailability of a sufficient number for several intensities of earthquakes make its results questionable (Rota et al. 2008). Due to the low frequency of occurrence, few datasets are available either for low and very high-intensity events, making difficult to choose representative cumulative density functions to define fragility curves (Kappos et al. 2006).

Different studies based on empirical approaches to estimate seismic vulnerability in Italy have been presented in literature (Di Pasquale et al. 2005, Rota et al. 2008, Zuccaro and Cacace 2015, Del Gaudio et al. 2019, Donà et al. 2020, Polese et al. 2020). Among these, Rota et al. (2008) developed an extensive study based on statistical processing of damage data relating to 150,000 Italian residential buildings interested by earthquakes (from 1980 Irpinia's to 2002 Pollino and Molise's earthquake) aimed at developing the fragility curves. A conspicuous number of buildings classes (about 16 for masonry buildings), differentiated as a function of masonry types, floors and the number of storey is resulted.

Recently, Del Gaudio et al. (2019) defined empirically-derived typological fragility curves for masonry buildings after the 2009 L'Aquila's earthquake based on damage data of 32,520 residential buildings. Twenty buildings classes differentiated for masonry type, vertical and horizontal structural arrangement resulted, and typological fragility curves were developed in compliance with the damage levels defined by European Macroseismic Scale (*EMS98*).

In the case of mechanical methods, fragility curves are the result of statistical elaboration of data derived from numerical analyses performed on case study buildings, real or simulated through Monte Carlo stochastic analyses (Rota et al. 2010, Belliazzi et al. 2021). With respect to empirical methods, mechanic-based approaches could result more effective when a large dataset of information on buildings features are available. In the face of an amount of data, the use of simplified structural models aimed at reducing the computational effort for both in-plane and out-of-plane analyses is justified, but taking into account that uncertainties related to approximations in the structural modelling and on the material properties can affect negatively the structural response (Rota et al. 2014, Quagliarini et al. 2017, Sandoli et al. 2020).

Expert-judgement methods provide typological fragility curves from statistical processing of information provided by a team of experts which estimate feasible damage level and structural behaviour for structures with different characteristics. This necessitates, on one side, of an appropriate knowledge of the constructional techniques and structural features of buildings stock and, on the other side, mastery of the theoretic structural behaviour. *ATC-13* (*ATC-1985)* standards demonstrated that judgement-based approaches could over-estimate the structural damage and the results could be affected from the sensibility and technical knowledge of the method developer.

To overcome the limitations inherent in each method, hybrid methodologies are often preferred by researchers. A macroseismic approach based on combination of empirical data and expert-judgement was presented in Bernardini (2004), while a mixed macroseismic and mechanical model was proposed in Lagomarsino and Giovinazzi (2006). In the latter, the vulnerability of building's classes is defined through vulnerability curves, within the macroseismic method, and through capacity curves within the mechanical method. Again in 2006, Kappos et al. (2006) presented a hybrid method to develop fragility curves for masonry and reinforced concrete buildings in Greek; the method combines statistical data derived from earthquake-damaged constructions with the results of nonlinear static or dynamic analyses conducted on a large number of building types.

Recently, a mixed mechanics-based fragility model for Italian unreinforced masonry building was proposed by Donà et al. (2020). Based on information derived from National Institute of Statistics (*ISTAT*) in combination with expert-judgment observational procedure. It divided residential unreinforced masonry (*URM*) buildings in ten classes by age of construction and number of storeys. The software Vulnus 4.0. processes information on buildings features, material strength, types of floors, etc., and calculates maximum bearable Peak-Ground Acceleration (*PGA*) used to derive fragility for the defined classes.

1.1 Research significance

This paper presents a hybrid methodology to define typological fragility curves valid for territorial or regional scale seismic vulnerability assessment, based on the combination of the mechanical and expert-judgment approaches. The judgment-based part classifies the Italian *URM* buildings into five homogeneous structural-typological classes, while the mechanical part defines the numerical parameters for developing the fragility functions.

The proposed classification is the result of an observational approach that matches the authors' experience developed in post-earthquake surveys (of the last forty years) with information available in literature. It arises on a close correlation among *i*) age of construction (in turn related to the evolution of the seismic Codes over the years), *ii*) structural characteristics of the buildings (i.e., material types, horizontal and vertical structures, seismic devices, etc., and *iii*) seismic behaviour and damaging observed in post-earthquake situations. Together, these three factors contribute to define the overall *seismic behaviour*, considered the real discriminant that allows the subdivision in typological classes (Calderoni et al. 2020, Sandoli and Calderoni 2021).

For each building class, results of numerical analyses on buildings prototypes, in part performed by the authors on real case studies and in part found in literature, have been together collected aimed at elaborating a database to define the fragility curves. *PGA* bearable by each building class at Ultimate Limit State has been chosen as the main Intensity Measure (*IM)* to represent fragility curves.

To have a more reliable and complete representation of the seismic vulnerability, a range of variability of the fragility curves has been considered: three different curves have been developed for each building class, differentiating the statistic variables as a function of mean, maximum and minimum bearable *PGA*s.

Such curves have been also correlated with the Mercalli-Cancani-Sieberg (*MCS*) intensity scale, allowing for a representation of the expected damage scenario for increasing seismic intensities.

Results showed that the proposed methodology gives rise to realistic typological fragility curves, representative of the seismic vulnerability and damage scenario observed for *URM* Italian building stock after seismic events. Moreover, fragility curves derived via hybrid method have been also compared with those obtained with empirical method (i.e., based on *EMS98*) and the differences highlighted.

2. Methodology

Hybrid methods are recognized as effective solutions to develop fragility model. In the proposed methodology expert-judgment with mechanical approaches are combined: the first provides a structural-typological classification of the Italian buildings as a function of the recurrent types on the territory, while the second provides the mechanical parameters necessary to elaborate fragility curves. In Fig. 2 a conceptual map of the adopted methodology is represented, indicating the contribution made by each approach, while in the following the adopted methodology is described.

2.1 Expert-judgment contribution

To divide residential *URM* buildings in a reduced number of homogeneous typological classes representative of the whole Italian buildings stock plays a crucial role to develop fragility models usable on the whole National territory with minimum effort and errors.

Key issue is that the term ‘masonry building’ includes a very large set of buildings, each characterized by different material properties, structural features (i.e., seismic-resistant devices, floors, roofs, etc.) and details. As a consequence, their structural behaviour under seismic actions can be also significantly different on each other.

Despite these differences, a fairly close correlation among the *age of construction*, *structural typology* and *observed seismic behaviour* and *damaging* after earthquakes does exists (Di Ludovico et al. 2017, Calderoni et al. 2020, Sandoli and Calderoni 2021). They represent the key factors for defining the classification and together contribute to define and to differentiate the *global seismic behaviour* of the buildings typologies. This latter is considered as the real discriminant of the classification that provides the subdivision in structural-typological classes (Fig. 3).

The classification is the result of the in-field authors’ experience developed in the aftermath of the most severe earthquakes occurred in the last forty years in Italy, combined with the research activity conducted in academia. Even if in different ages, the authors have been involved by the Italian Department of Civil

Protection (*DPC*) in the activities aimed at post-seismic usability and damage assessment of buildings hit by earthquakes. Moreover, they are now engaged in the *CarTiS* research project (promoted in collaboration between *DPC* and *ReLUIS*) whose scope is that of mitigating the seismic risk in Italy.

Such activities allowed observing damaged buildings closely and to correlate the type of damage to both structural features and ages of construction. Part of such activities are documented in specific scientific papers, e.g. Calderoni et al. (2011), Di Ludovico et al. (2017), De Martino et al. (2017) and Calderoni et al. (2020).

Moreover, technical manuals or books (Pagano 1967, Baila et al. 2011, Ghersi et al. 2011), restoration and consolidation manuals (Mastrodicasa et. al 1943, Carbone et al. 2001) and past Italian Codes have been also examined to ensure a correct representativeness of the proposed typologies with respect to the buildings diffused on the whole territory. This allowed for a better correlation between structural typologies, constructional techniques, types of material, methods of interventions, structural details, and ages of construction.

Age of construction is probably the most relevant aspect for the differentiation in typological classes. In the majority of literature papers, time intervals are defined as those between two consecutive *ISTAT* (National Institute of Statistics) census; thus, the first buildings class refers to constructions erected before 1918, the second collects buildings erected from 1919 to 1945 and so on up to constructions built after 2001 (Del Gaudio et al. 2019, Rosti et al. 2020). This is an effective way for identifying the buildings' constructional features included in the *ISTAT* database (e.g., type of materials and number of storey) but it does not take into account the years of emanation of the Codes in an explicit way.

Dates of Codes emanation are important because new constructional rules or structural details were time to time introduced, often decisive to differentiate the global seismic behaviour of the constructions. In the proposed classification, ages of construction are recognized as a function of the years of introduction of new Codes or other specific Regulations. Typically, new Codes were released after significant seismic events and could assume local (i.e., limited to the zones affected by earthquakes) or National valence.

Such ages represent a basic time interval valid for all Italian Regions, but can be susceptible to modifications depending on specific requirements due to the municipal urban planning or other special events that have interested a specific area. Then, further time intervals and/or new structural typologies can be added when necessary for assessing the seismic vulnerability of an area.

Anyhow, the *ISTAT* database has been analysed and elaborated to highlight the evolution of masonry buildings both in Italy (Fig. 4*a*) and in its macro-Regions (north-west, north-east, centre and south - Fig. 4*b*) over the years. By looking at Fig. 4*a* and 4*b*, the great part of masonry buildings date back before the second world war, with a great concentration of them before 1918. During the post-war reconstruction (i.e. 1960-1970) the number of masonry buildings decreases in the face of other structural typologies, that in Italy consist almost totally of reinforced concrete buildings.

Structural typology regards the structural arrangement of the constructions, including type of horizontal and vertical structures. According to literature, types of floors have been differentiated as a function of the material, having in mind that different materials could require diverse structural solutions that in turn influence (or change) the overall seismic response of the construction.

Basically, in historical constructions, floors consist of in-plane deformable structures made with masonry vaults or timber/iron beams, while in modern buildings, floors consist of in-plane rigid elements made with reinforced concrete or steel beams and provided of an upper reinforced slab.

With respect to other literature works, vertical walls assume a different significance in this paper. In the great part of the literature papers, masonry material is identified as the key parameter which rules the seismic response of the constructions and, consequently, governs the typological classifications *(EMS98*). While in others, masonry material assumes less importance, representing an element strictly correlated to the age of constructions (Donà et al. 2020).

The authors believe that the seismic behaviour of the buildings depends above all on the structural-typological characteristics of the construction, intended as effectiveness of wall-to-wall or wall-to-floor connections, amount of in-plane stiffness of floors, presence of ties, geometry of piers and lintels, amount of gravity loads, etc. Conversely, the intrinsic properties of materials and their arrangement can improve or worsen the basic seismic behaviour without modifying the seismic capacity of the constructions significantly (Sandoli and Caderoni 2021). Anyway, it is evident that, on equal terms, the better the masonry properties and quality the more the structure can resist to seismic actions.

Furthermore, the authors believe that the correlation between type of masonry material and ages of construction is not at all valid for the Italian Regions (especially if referred to historical constructions), because in Italy the type of masonry is strictly related to the materials available in the geographical area of reference. As an example, in the Central Apennine area irregular calcareous stones were mainly used, while in the South and North Apennine tuff stones and clay-bricks respectively. Similarly, also the type of mortar changes Region by Region: in South Apennine pozzolanic-based mortar was used most, while lime mortar in North-Central zones (ISPRA 2021).

In the proposed classification, masonry material has been regarded as a factor which can enhance or worsen the basic structural behaviour of the structural typology. However, type of used material as a function of the geographic area have been specified for each buildings class (see Appendix).

In the perspective of an observational approach, either observed *seismic behaviour* and *damaging* following to an earthquake are fundamental for including buildings with similar features into the same typological class. Post-earthquake inspections allowed to identify the role played by technological features and structural details on the overall seismic behaviour of the construction and to differentiate the buildings typologies. A strict correlation between observed seismic behaviour/damaging and age of emanation of Codes has been also noted, in fact rules introduced by the Codes changed the nature of the buildings and diversified their seismic response.

2.2. Mechanical contribution

Based on numerical analysis, the mechanical approach provides the parameters for developing the fragility functions and represents also an effective support to validate the buildings' classification.

Aimed at evaluating representative *IM* parameters required to derive the fragility curves, results of nonlinear analyses have been collected in advance. They can come from analyses on real case study buildings or statistical simulations (i.e., Montecarlo analysis).

In this paper results referred to real case studies have been preferred, because considered more representative of the structural features of the constructions with respect to statistical simulations.

3. Evolution Of The Seismic Codes In Italy

The evolution of seismic Regulations in Italy is related to the occurrence of catastrophic events. In Table 1 is reported an historical overview of the Italian seismic Codes, together with the relative precursor seismic event, the geographic area and the types of buildings to which the Codes were referred to.

Before listing the various Codes, it is interesting to premise that untill 1987 (Ministerial Decree DM 1987) no specific design rules were provided in Italy for masonry buildings and only rules-of-art handed by the masons over the years were included in the Codes. Nevertheless, the analysis of the past seismic standards is important for defining the main structural features of masonry constructions as a function of the age of the construction.

The first basic design rules for masonry buildings were introduced by the Royal Decree RD 1909, after the 1908 Messina and Reggio Calabria's earthquake. RD 1909 - which can be considered as the precursor of the 'modern' seismic Codes - provided requirements for reconstruction and repairing of damaged masonry buildings, valid in those areas hit by earthquake only. It included specific rules aimed at preventing the intrinsic vulnerabilities of existing buildings (mainly out-of-plane failure modes) and was the first Italian document that defined a method for calculating the horizontal seismic actions as a function of the building's masses. Similarly, after the 1915 Avezzano's, 1919 Mugello's and 1920 Garfagnana's earthquakes relative RDs were introduced for the reconstruction process of those areas (Tab. 1).

Common to all these Codes, they were drafted on the basis of observed damage and limited the use of vulnerable elements that caused collapse of the buildings such as: masonry vaults (except for the ground floor), cantilevered stairs, arches, poor quality masonry or thrusting roofs. Moreover, such Codes disposed the adoption of metal-ties for preventing out-of-plane failure modes of the façade walls for the first time. It is interesting to point-out that metal-ties were suggested not only for strengthening damaged existing buildings, but also for new constructions. Concerning the new constructions, maximum building's height, number of storeys, minimum thickens of the walls and minimum distances among resistant-walls were also provided.

These prescriptions were substantially confirmed in all the subsequent codes released after the 1930 Irpinia's and 1936 Veneto-Friuli's earthquakes, and were valid in all those areas classified as 'seismic' by the RD 1927.

In the history of the Codes, a crucial date is represented by 1937. In this year, it was released the RD 1937, mandatory for all Italian Regions, which introduced new important constructional rules for masonry buildings that changed the way of conceiving the masonry structures: in fact, reinforced concrete ring beams and reinforced concrete floors (provided of top reinforced slab) became mandatory at each floor level for new masonry constructions. This date marks a crossing point from old (or 'ancient') to 'modern' masonry buildings, both characterized by a significantly different seismic behaviour (as better discussed in the Sect. 4). Despite that reinforced concrete elements were explicitly required for new constructions, no indication on minimum steel reinforcement percentages to include in the top slabs were provided by the RD 1937. The constructional rules for reinforced concrete slabs were introduced in the RD 1962 only, which provided indications on minimum slab's thickness and minimum transversal steel reinforcements. For the lintels over the opening, first regulations were introduced in the codes prior to 1962 in which (at least) 80 cm of anchorage inside the adjacent masonry was prescribed (but in the codes of 1962 this requirement was removed).

As shown in Tab. 1, after 1937 a series of codes were introduced as a consequence of new seismic events. Regarding the anti-seismic provisions, the main core of these documents remained the same of the RD 1937. But new indications regarding geometrical limitation of the structural elements or to the building arrangement were time by time introduced. For instance, blocks holes' ratio appeared in the DM 1975, while hollow blocks compressive strength in the DM 1984. Again, limitations about both vertical dimensions (maximum height of the building, maximum inter-story height and maximum storey number) and horizontal dimension (maximum distance between load-bearing walls, maximum distance between wall and buttress, minimum wall thickness, and minimum buttresses width and thickness) were introduced in DM 1996, as well as the maximum walls' slenderness (defined as the ratio between thickness and height of the wall) and their minimum cross-section enlargement at different storey.

Finally, in the modern Codes, i.e. introduced from 1996 onwards, more detailed indications concerning the seismic design of new masonry structures and methods for seismic assessment of existing ones have been enclosed.

Table 1. Evolution of the Italian seismic Codes.

Seismic event	*Code's name*	*Validity*	*Type of buildings*
Messina and Reggio 1908	RD 1909	Area hit by earthquake	New and existing
Avezzano 1915	RD 1915	Area hit by earthquake	New and existing
Mugello 1919	RD 1920	Area hit by earthquake	New and existing
Garfagnana 1920	RD 1921	Area hit by earthquake	New and existing
Irpinia 1930	RD 1935	Area hit by earthquake	New and existing
Veneto-Friuli 1936	RD 1937	All Italian Regions	New
Irpinia 1962	L 1962	All Italian Regions	New
Belice 1968	DM 1975	All Italian Regions	New
Irpinia 1980	DM 1981	All Italian Regions	Existing
	DM 1987	All Italian Regions	New
	DM 1996	All Italian Regions	New and existing
Umbria Marche 1997, Molise 2002	IBC 2008 and relative Recommendations	All Italian Regions	New and existing
L'Aquila 2009, Emilia 2012, Central Italy 2016-17	IBC 2018 and relative Recommendations	All Italian Regions	New and existing

4. Structural-typological Classification Of Urm Buildings

Five different typological (or vulnerability) classes, indicated with the acronyms from *URM-1* up to *URM-5*, have been considered as representative of the recurrent Italian residential *URM* buildings.

A description of the five building's classes is reported in the following, while an Appendix containing detailed information on ages of construction, types of floors and of materials (as a function of the geographic zones) is reported at the end of the paper.

4.1 Ancient Buildings

The class of the '*Ancient Buildings*' (*URM-1*) includes the constructions erected before of the first decade of the 20th century and represents the prevalent typology in the Italian historical centres. In the majority of cases they were fabricated in compliance with the empirical rules in force at that time of construction, handed down by oral tradition.

Ancient Buildings consist of load-bearing masonry walls and floors made with masonry vaults or wooden/iron parallel beams simply supported on the walls. The poor effectiveness (or sometimes the absence) of connections between façades and transversal walls and between walls and floors, makes the perimetral walls (or portions of them) prone to out-of-plane failure mechanisms under seismic actions. This behaviour, typical of ancient constructions, has been recognized in almost all the Italian historical centres affected by medium and high-intensity seismic events (Calderoni et al. 2011, Penna et al. 2014).

In Fig. 5 are represented two Ancient Buildings damaged during the 2009 L'Aquila (Italy) earthquake. In Fig. 5*a* a two-storey masonry building made with full-height masonry walls and thin-walled vaults at each level is represented. Vertical cracks in the corners of the building denote the activation of out-of-plane mechanisms, while some internal masonry vaults are collapsed (further details concerning the damage state are reported in Sandoli and Calderoni 2021). Instead, Fig. 5*b* illustrates the case of an Ancient Building having wooden floors and hit by the 2016 Central Italy earthquake: due to the not effective wall-to-wall and wall-to floor connections, façade wall is collapsed out-of-plane. Moreover, the crumbled masonry at the foot of the building allows to imagine that also the bad masonry quality has furtherly aggravated the seismic response of the entire construction.

This class contains buildings that have not been subjected to seismic retrofit interventions over the years, although today located in seismic-prone areas as a consequence of the latest seismic macro-zoning of the Italian territory released by Italian Building Code (IBC-18), that declared the whole territory as seismic.

In detail, *URM-1* buildings have been erected before of 1937 in non-seismic zones and before of the year of emanation of the specific seismic Codes for the zones affected by earthquakes from 1909 to 1937. As highlighted in the Sect. 3, 1909 and 1937 are two dates of fundamental importance for the evolution of seismic Codes in Italy: (*i*) the RD 1909 is the first document that provided requirements for strengthening and repair of damaged masonry buildings (even if limited to the zone of Messina and Reggio Calabria hit by earthquake) introducing rules aimed at preventing the main intrinsic vulnerabilities of masonry buildings (i.e., out-of-plane of the façade walls) , (*ii*) 1937 represents the year in which no Ancient Building could be erected in Italy as a consequence of the introduction of a new Regulation (RD 1937).

4.2 Improved-Ancient Buildings

The occurrence of earthquakes and the introduction of new Codes (even if limited to a restricted geographic area) led to the typology of the *Improved-Ancient Buildings* (*URM-2*). It collects buildings erected before of 1937 in non-seismic area and those constructed before of the year of emanation of the specific seismic Codes for zones hit by earthquakes from 1908 to 1937 (declared as seismic following to earthquakes), but which have been subjected to retrofit interventions as a consequence of seismic damaging. Thus, basic materials and structural features remain the same of *URM-1*, except for retrofit interventions.

Thanks to the introduction of tie systems and/or similar anti-seismic devices, the connections between orthogonal walls and between floors and walls were improved. Post-interventions, seismic performances of the constructions change significantly: it is no longer ruled by out-of-plane but by in-plane strength, stiffness and ductility of piers and spandrels (despite that floors remain deformable in-plane) (Tomazevic 1999, Magenes et al. 2014, Calderoni et al. 2016a).

Such behaviour has been observed on Improved-Ancient Buildings hit by 2009 L'Aquila or 2016 Central Italy events, where ruinous collapses have been prevented thanks to the adoption of steel-ties. Also, numerical analyses confirmed the enhancement of the seismic performances of the strengthened buildings, because considerable increases of seismic capacity and damage reduction in comparison with unstrengthen constructions (*URM-1*) resulted.

Two examples of *URM-2* buildings, strengthened with steel-ties, and damaged by the 2009 L'Aquila earthquake are represented in Fig. 6. It shows piers and spandrels interested by in-plane diagonal cracks as evidence of the activation of an in-plane behaviour under seismic actions.

4.3 Modern Buildings

After the 1908 earthquake, to prevent further human and economic losses and to ensure higher safety levels concerning future events, a new Royal Decree was emanated in 1937 (RD 1937).

This Regulation becomes mandatory for all the Italian Regions (either seismic or not) and contains anti-seismic constructional rules regarding new buildings. It legitimized the birth of the *Modern Buildings* (*URM-3*), recognized as the seismic-resistant solution within the current seismic Codes still today (IBC-18). Starting from this date onwards Ancient Buildings could not be erected anymore in Italy because no-code conforming.

RD 1937 was a revolutionary Code because it changes the structural conception of the buildings. New rules addressed towards a more performant box-like behaviour under seismic actions: explicit reference to floors made with reinforced concrete elements appeared for the first time, adoption of reinforced concrete ring beams effectively connected to both floors and walls became mandatory at each story, as well as lintels effectively connected to the adjacent piers were required.

The introduction of in-plane stiff floors (i.e., provided of top reinforced slab) and reinforced concrete ring beams represented an important measure for the seismic safety of masonry buildings. The latter interrupted the vertical continuity of the walls at each story and limit the possibility of out-of-plane mechanisms to the inter-story height of the buildings (e.g., out-of-plane flexure). The walls are forced to behave in-plane and their seismic resistance depends on geometry of piers and spandrels, level of gravity load, constrain conditions and mechanical properties of materials (Tomazevic 1999, Gesualdo et al. 2019). Moreover, the presence of in-plane rigid diaphragms allows to share the seismic forces among the walls as a function of the in-plane stiffness, instead of as a function of the tributary area as in the case of *URM-2*.

The effectiveness of these provisions and the satisfactory seismic behaviour of the Modern Buildings has been demonstrated after main subsequent earthquakes. L'Aquila and Irpinia's, as well as Friuli's earthquakes, proved that global collapses were very rare and limited also for high-intensity earthquakes and imputable to constructional defects when occurred. An extensive analysis on the seismic behaviour and damaging of Modern Buildings is reported in Calderoni et al. (2020) with reference to 2009 L'Aquila's earthquakes; while, for Irpinia's and Friuli's earthquakes a detailed discussion is reported in Pagano (1990) and in Tomazevic (1999), respectively.

Also numerical analyses performed on real case study buildings highlight the good seismic performance and the achievement of significant seismic capacity of *URM-3* building's typology (Calderoni et al. 2016, Lagomarsino et al. 2019).

Modern Buildings include not only constructions erected after the 1937 in non-seismic zones, but also those constructed according to the specific Codes issued from 1909 onwards for the zones affected by earthquakes (declared as seismic zones in advance).

Two earthquake-damaged Modern Buildings, the first located in L'Aquila and the second in San Severino Marche (hit by 2016 earthquake) are represented in Fig. 7. In both cases the seismic provisions required by RD 1937 have inhibited out-of-plane mechanisms, constraining the construction to behaves in-plane: diagonal-cracks extended from r.c. rings up to the bottom of piers are clearly recognizable.

4.4 Semi-Modern Buildings

Ancient, Improved-Ancient and Modern masonry buildings represent the most diffused typologies on the Italian territory. Despite this, in the zone hit by earthquakes between 1909 and 1937 and however before of 1937 in non-seismic zones, it is not uncommon to find hybrid typologies, here indicated as *Semi-Modern Buildings* (*URM-4*).

URM-4 buildings are erected in a transition age that marks the passage from Ancient or Improved-Ancient to Modern Buildings, i.e. constructed in the period necessary for making mandatory the Codes released in the zones interested by earthquakes. As a result, new anti-seismic constructional rules were not all respected, even because not fully known by the workers.

Floors are made with reinforced concrete or steel beams - provided or not of a reinforced slab - poorly connected to the vertical walls. Although reinforced concrete or steel ring beams are connected with continuity on the perimeter of the walls, they were often not placed at the floor levels and then not directly connected to the floors themselves. On the other side, reinforced concrete ring beams are however effective to limit local out-of-plane mechanisms. Due to their structural arrangement, seismic behaviour of Semi-Modern Buildings can be considered slightly better than Improved-Ancient buildings but worse than Modern Buildings.

In Fig. 8 is reported an example of Semi-Modern (school) buildings located in Naples, dating back to the 1920*s*: it can be noted that reinforced concrete ring beam is positioned above the windows opening and not at floor level.

4.5 No Code-Conforming Buildings

The fifth class is represented by the *No Code-Conforming Buildings* (*URM-5*). It includes buildings not designed in compliance with the Standards in force at the age of construction, even if erected before of 1937 but after the year of emanation of the corresponding Codes for the zones affected by earthquakes from 1908 to 1937, or after to the emanation of RD 1937 in non-seismic zones.

Due to their aesthetic (and age of construction), *URM-5* buildings appear to be similar to Modern Buildings, but the structural behaviour is completely different from the latter. The absence of ring beams or equivalent anti-seismic devices makes wall-to-floor and wall-to-wall connections not effective. Consequently, their seismic behaviour can be assimilated to that of Ancient instead of Modern Buildings because ruled by out-of-plane mechanisms.

In Fig. 9 is represented an example of No Code-Conforming Building located in Emilia Romagna Region and damaged by the 2012 earthquake. From one of the external sides, a large crack that crosses the inter-story level (both at first and second story) is visible, while in the internal side a wide horizontal crack at wall-to-floor interface can be noted; such cracks prove the absence of effective wall-to-wall and wall-to-floor connections.

5. Method For Deriving The Fragility Curves

In this Section, the methodology to derive typological fragility curves for each building's typology is discussed. Fragility defines the conditional probability of being in or exceeding a particular Damage Measure (*DM*) given an Intensity Measure (*IM*) of the earthquake.

Usually, three different groups of parameters to represent the *IM* are used: *a*) Peak Ground parameters, in terms of Acceleration (*PGA*) or Velocity (*PGV*); *b*) elastic spectral acceleration or displacement; *c*) macroseismic intensities scales.

As a drawback, studies demonstrate that the Peak-Ground parameters are not related to the earthquake's frequency content, duration and number of cycles (Rossetto et al. 2013). On the other hand, spectral values depend on the equivalent vibration period of the structure and a single value cannot be representative for all buildings (also within the same class). Macroseismic scales, instead, can result poorly representative for low and high-intensity seismic events (as discussed in Sect. 1).

Damage Measure (*DM*) is generally expressed in terms of probability of exceeding an established Limit State, i.e. achievement of maximum displacement capacity (ultimate rotation, maximum inter-story drift, etc.) in one or more structural elements.

In this paper *PGA* has been employed as the *IM* of the earthquakes, intended as the maximum ground motion bearable by the structure at *ULS* measured on soil-type *A (i.e., on the bed-rock) defined by IBC-18*. Independently from soil properties and its geographical location on the National territory, soil-type *A* gives an objective measure of the seismic capacity of the construction as a function of its structural arrangement. Obviously, soil amplification factors defined by the Codes must be applied to obtain a realistic measure of seismic fragility depending on soil characteristics of the investigated area. Furthermore, analytical correlation between *PGA* and *MCS* macroseismic scale has been exploited to represent fragility curves in terms of *MCS* intensity. Such curves measure the severity of an earthquake as a function of damage level inflicted on the buildings by the earthquakes and feeling felt by peoples.

MCS scale was firstly calibrated by the seismologist Giuseppe Mercalli on Italian earthquakes and subsequently detailed (enlarged) for assuming European significance (i.e., effects produced by other European earthquakes on buildings were included). Being calibrated on features of Italian earthquakes and damaging suffered by Italian buildings, *MCS* has been considered as a representative intensity measure within the research purpose.

As *DM* the attainment of *ULS* condition by the structure has been chosen. It corresponds to the achievement of the maximum drift of the structural elements when dominated by an in-plane behaviour of the walls, and to the activation of overturning mechanisms in case of out-of-plane response.

5.1 Dataset for derivation of fragility curves

The proposed fragility model is valid for the large-scale vulnerability assessment of typical Italian masonry building stock. For this reason, it refers to low-rise masonry buildings having a number of storeys ranging from 2 to 4.

Values of *IM* and the related statistic variables used to define the fragility functions have been obtained through a mechanical approach. Data relative to a sufficient number of numerical analyses results conducted on masonry building prototypes have been collected and analysed to define a database. Such results come in part from previous analyses conducted by the authors on real case study buildings and in part have been found in literature. Some of the papers or books used to elaborate the dataset are the following: Ghersi et al. (2011), Rota et al. (2014), Calderoni et al. (2016a), Calderoni et al. 2016b, Cattari et al. (2018), Lagomasino et al. 2019, Morandi et al. (2020) Sandoli and Calderoni (2021). Each analysed building has been recognized as belonging to one of the five typological classes defined in Sect. 4. For each of them the maximum, minimum and mean values of the bearable *PGA* - together with coefficients of variation and standard deviations - have been evaluated. It should be underlined that the collected data are surely less than those used within the empirical method, but considering that numerical analyses are based on real material properties, real geometry and loads, such data are more realistic in comparison with empirical or mechanical-statistical (i.e., Monte Carlo simulation) evaluations.

Tab.2 indicates minimum and maximum and mean values of *PGAs* (expressed as a percentage of the gravity acceleration *g*), standard deviations (s) and coefficients of variation (*CoV*) for each typology. Note that values of s are different for each class because directly related to *PGA*s, while coefficients of variation remain unchanged because of taking into account for modelling and material uncertainties and for different structural arrangements of buildings (even belonging to the same typological class).

Methods to calculate the *PGA*s are those suggested by IBC-18 and ISR-19 (coherently with the Eurocode 8): *i*) linear or nonlinear kinematic analyses for buildings prone to out-of-plane behaviour and *ii*) nonlinear static or dynamic analyses for buildings dominated by in-plane behaviour.

As it can be noted in Tab. 2, Ancient Buildings (*URM-1*) represent the most vulnerable typology, while Modern Buildings (*URM-3*) are those characterized by higher values of *PGA*. This difference is due to the bad seismic behaviour of Ancient Buildings, governed by out-of-plane mechanisms, with respect to the good seismic response of Modern Buildings, characterized by a box-like behaviour. Semi-Modern Buildings (*URM-4*) show *PGA*s ranging between *URM-2* and *URM-3*, confirming their hybrid nature. Conversely, structural deficiencies listed in the Sect. 4 for No Code-Conforming Buildings (*URM-5*) negatively affect their seismic behaviour, making them similar to the Ancient Buildings.

*PGA*s relative to *URM-1*, as well as those of *URM-4* and *URM-5*, are affected by the higher coefficient of variations. This mainly depends on the greater uncertainties related to *i*) a not well-defined structural behaviour of the walls, *ii*) the assumptions made for structural modelling of the macro-elements for the out-of-plane analyses, *iii*) the choice of the actual failure mechanisms among those admissible, *iv*) constraint conditions of the walls and *v*) conventional and constant value of behaviour factor adopted to take into account the (reduced) ductile and dissipative response related to out-of-plane response (assumed equal to 2.0 by ISR-19).

On the contrary, fewer dispersions affect the results relative to the typologies *URM-2* and *URM-3* because they are characterized by a clearer in-plane structural behaviour, despite the assumption made for defining the structural models. In these cases, *PGA*s are calculated on the basis of pushover analyses adopting the *N2* method (Fajfar and Gaspersic 2000), in which pushover curve of the multi-degree of freedom structures is transformed into an equivalent bilinear curve relative to a single degree of freedom system and the behaviour factor is calculated as a function of the available ductility of the structure (but however limited to 3.0 by ISR-19 and Eurocode 8).

Anyway, also for *URM-2* and *URM-3* the coefficients of variation remain considerable, because modelling uncertainties can affect significantly the in-plane behaviour of the walls (Rota et al., 2014).

Concerning to correlation of *PGA* with *MCS* scale, it is described in Section 6.2.

Table 2. Data for deriving fragility curves

Structural typology		Minimum		Maximum		Mean	
	CoV	PGA/g	s	PGA/g	s	PGA/g	s
	(%)	(-)	(-)	(-)	(-)	(-)	(-)
URM-1	60	0.04	0.024	0.10	0.060	0.070	0.0420
URM-2	50	0.10	0.050	0.15	0.075	0.125	0.0625
URM-3	40	0.12	0.048	0.20	0.080	0.160	0.0640
URM-4	60	0.12	0.072	0.18	0.108	0.150	0.0840
URM-5	70	0.05	0.035	0.12	0.084	0.085	0.0595

5.2 Fragility function

To process the data listed in Tab.2, a Lognormal statistical distribution has been adopted. Literature works demonstrate that this distribution fits correctly empirical or numerical data and that it provides, with sufficient approximation, feasible vulnerability scenarios (Del Gaudio et al. 2019, Donà et al. 2020, Rosti et al. 2020).

Probability Density Function (*PDF*) of the Lognormal distribution is given by the following formula:

$$PDF = \frac{1}{IM\mu\sqrt{2\pi}} \exp\left[-\frac{1}{2}\left(\frac{\ln IM - \mu}{\beta}\right)^2\right] \tag{1}$$

Eq. (1) gives back an asymmetric Gaussian bell-curve whit a peak corresponding to the lognormal mean value and which tends to zero at both ends of the curve itself. Coefficients b and m are the standard deviation and the mean value of the lognormal distribution, respectively. They are related to the standard deviations (s) and values of *PGA* (minimum, maximum or mean) of the Normal distribution listed in Tab. 2 through the correlation formulas reported in the following:

$$\beta = \sqrt{\ln\left(\frac{\sigma^2}{PGA} + 1\right)} \tag{2}$$

$$\mu = \ln(PGA) - \frac{\beta^2}{2} \tag{3}$$

Tab. 3 groups the values of b and m calculated through the eqs. (2) and (3), respectively.

The Cumulative Density Function (*CDF*) - i.e. the conditional probability of being in or exceeding a particular *DM* given an *IM* of the earthquake - provides the fragility curve. It is obtained by integrating eq. (1):

$$CDF = P[DM > dm \mid IM] = \frac{1}{2} + \frac{1}{2} erf\left[\frac{\ln IM - \mu}{\beta\sqrt{2}}\right] \tag{4}$$

Table 3. Values of mean (m) and standard deviation (b) of the Lognormal distribution

Structural typology	*Minimum*		*Maximum*		*Mean*	
	m	*b*	*m*	*b*	*m*	*b*
URM-1	3.622	0.307	4.538	0.307	4.182	0.307
URM-2	4.561	0223	4.967	0.223	4.784	0.223
URM-3	4.757	0.148	5.268	0.148	5.044	0.148
URM-4	4.721	0.307	5.126	0.307	4.944	0.307
URM-5	3.813	0.398	4.688	0.398	4.343	0.398

6. Typological Fragility Curves At Uls For The Five Buildings Classes

6.1 Fragility curves in terms of PGA

Fig. 10 reports *PDF*s and *CDF*s obtained by using as *IM* the logarithmic values of *PGA* at *ULS* defined through the eq. (3). IBC-18 (as well as Eurocode 8) defines *ULS* as the state in which ‘after an earthquake, the structure shows heavy damage to the structural elements but preserves a sufficient safety factor against gravity loads and an exiguous safety factor with respect to horizontal actions’.

Each graph of Fig. 10 consists of three curves: the first (continuous line) refers to logarithmic coefficients of variation and standard deviations calculated on mean values of *PGA*s, while the other two (dashed lines) refer to logarithmic coefficients of variation and standard deviations evaluated on minimum and maximum value of *PGA*s.

To include a range of variability represents a more complete way for representing fragility curves and estimating likely vulnerability scenarios. Such variability arises from the fact that each typological class groups buildings having structural arrangement coherent with the age of construction but, due to different structural features, details and material properties, their seismic vulnerability can be different also within the same buildings class.

In Fig. 11*a* and 11*b*, probability and cumulative density functions of the five structural-typological classes of Italian *URM* buildings are compared among them. The figure highlights that going from the typology *URM-1* to *URM-3* the curves are spaced and shifted onward: with reference to a 50% of probability of exceeding (*CDF*) seismic capabilities increased up to 3 times passing from *URM-1* to *URM-3*. Even more interesting is the significant gap between the fragility curve of *URM-1* with respect to *URM-2*, underlining the greater seismic vulnerability of the Ancient Building with respect to Improved Ancient Buildings.

Without any specific reference to the *PGA* values, which are based on a conventional calculation, preliminary and general observations on seismic vulnerability assessment at territorial-scale can be given. Fragility curves evidence that: *a*) the high level of seismic vulnerability of an area is conditioned by the percentage of Ancient Buildings contained in it; *b*) light and low-invasive strengthening interventions (such as ties) can reduce significantly the seismic vulnerability at territorial scale because they change the structural behaviour from *URM-1* to *URM-2*. It is evident that, to obtain a significant reduction of seismic vulnerability with a lower expense, a correct territorial-scale planning of interventions should prefer the adoption of light interventions.

6.2 Correlation with Mercalli-Cancani-Sieberg scale

Macroseismic intensity scales represent an important tool to evaluate seismic damage scenarios at territorial-level. *MCS* scale, as well as *EMS98*, takes into account of the severity of the earthquake as a function of both damage level produced to the buildings and feeling felt by peoples.

MCS scale includes 12 intensity degrees (from ‘instrumental’ to ‘apocalyptic’ earthquake) and describes the total damage of the buildings based on an observational approach, without specifying their structural features (Tab. 4). This fact - which might seem in contrast with the proposed classification - has been exploited to define a measure of the expected damaging for increasing levels of seismic intensity.

To this aim, a correlation between *MCS* and the structural typological classification herein proposed has been identified, and three damage levels for each building class were recognized. By reading Tab. 4, the typologies *URM-1*, *URM-2* and *URM-3* can be recognized in the *MCS* scale: *URM-1* are those defined as *poorly built* or badly designed constructions, *URM-2* are described as *well-built* ordinary structures and *URM-3* as *good designed* constructions. Moreover, it can be noted that the damage to buildings starts from Grade 6 (strong) up to Grade 11 (extreme), while effects on people and things are only considered before Grade 6. Three increasing levels of damaging, defined as *slight*, *considerable* and *great* are identified in *MCS* scale and associated to the buildings class for different damage Grades. Compared with the modern Codes for constructions, such levels of damaging can be identified as the Damage Limit State (*DLS*), Ultimate Limit State (*ULS*) and Collapse Limit State (*CLS*), respectively. A schematic representation of the association between typological classes and *MCS* intensity measure I_{MCS} (i.e. damage level) is reported in Tab. 5.

To obtain fragility curves in terms of I_{MCS}, correlation formulas between the *PGA* and I_{MCS} have been adopted. Different formulations are given in literature, all expressed as follows:

$$\log(PGA) = a + bI_{MCS} \quad (5)$$

where *a* and *b* are two coefficients provided in literature. In this study, *a*=-1.33 and *b*=0.20 suggested by Faccioli and Cauzzi (2006) have been adopted. Such coefficients are obtained by means of regression analyses referred to 27 records of Italian earthquakes and to the related damage survey.

In Fig. 12, fragility curves are represented with dashed lines in terms of I_{MCS} obtained adopting the coefficients provided by Faccioli and Cauzzi (2006). With regards to an average value of probability of exceedance (*CDF*=50%), it can be noted that they provide a little underestimation of damage level with respect to that expected from *MCS* scale (continuous line). As an example, for *URM-1*, at 50%, I_{MCS}= 5 is expected by Faccioli and Cauzzi's correlation, while I_{MCS}=6 is suggested by *MCS* scale. To better tune the correspondence between the Faccioli and Cauzzi's formula and the I_{MCS} index, the authors suggest to shift of one Grade the results provided by eq. (5), thus obtaining the curves with continuous line in Fig. 12.

Such fragility curves give a continuous representation of the probability of exceeding the ULS at each damage grade (from grade 1 to grade 12), separately for each building's class.

Note that in the case of methods based on statistical analyses of damage (i.e., empirical), the fragility curves referred to different Damage States or Limit States are easily representable (generally defined according to *DSs* defined by *EMS98*). In this paper, it was difficult to differently elaborate curves for each Limit State because results found in literature often do not allow to estimate reliable values of *PGA* corresponding to them.

The curves in Fig. 12 show that high-damage is predictable in almost all buildings typologies for earthquakes with I_{MCS} about of 8-9: this result reflects the post-seismic damage scenarios observed in Italy following to the most ruinous earthquakes. In fact, after the Irpinia's, L'Aquila's or Central Italy's earthquakes, all characterized by high values of I_{MCS} (Fig. 2), buildings resulted heavily damaged: *URM-1* totally or partially collapsed out-of-plane, while *URM-2* and *URM-3* heavily damaged in-plane (Calderoni et al. 2011, Penna et al. 2014, Calderoni et al. 2020).

As predictable, the expected damage scenario for the classes *URM-1* and *URM-5* resulted higher than *URM-2*, *URM-3* and *URM-4*, also in terms of I_{MCS}. Referring to mean values of I_{MCS} (between 6 and 8) the percentage of buildings *URM-1* and *URM-5* which will suffer damage is greater than *URM-2*, *URM-3* and *URM-4*. Moreover, the different damaging becomes more relevant for low values of I_{MCS} and less relevant for high values of I_{MCS} (where the curves tend to the asymptotic value of 100% of probability of exceedance).

Table 4. Mercalli-Cancani-Sieber scale

Grade	*Effect on buildings and peoples*
1 - *Instrumental*	Not felt by many people unless in favourable conditions
2 - *Weak*	Felt only by a few people at best, especially on the upper floors of buildings. Delicately suspended objects may swing
3 - *Slight*	Felt noticeably by people indoors, especially on the upper floors of buildings. Many do not recognize it as an earthquake. Standing motor cars may rock slightly. Vibration similar to the passing of a truck. Duration estimated
4 - *Moderate*	Felt indoors by many people, outdoors by a few people during the day. At night, some awakened.
5 – *Rather Strong*	Felt outside by most, may not be felt by some people in non-favourable conditions. Dishes and windows may break and large bells will ring. Vibrations like train passing close to house
6 - *Strong*	Felt by all; many frightened and run outdoors, walk unsteadily. Windows, dishes, glassware broken; books fall of shelves; some heavy furniture moved or overturned; a few instances of fallen plaster. Damage slight.
7 – *Very Strong*	Difficult to stand; furniture broken; damage negligible in building of good design and construction; slight to moderate in well-built ordinary structures; considerable damage in poorly built or badly designed structures; some chimneys broken. Noticed by people driven motor cars.
8 – *Destructive*	Damage slight in specially designed structures; considerable in ordinary substantial buildings with partial collapse. Damage great in poorly built structures. Fall of chimneys, factory stacks, columns, monuments, walls. Heavy furniture moved.
9 - *Violent*	General panic; damage considerable in poorly designed structures, wall designed frame structures thrown out of plumb. Damage great in substantial buildings, with partial collapse. Buildings shifted off foundations.
10 - *Intense*	Some well build wooden structures destroyed; most masonry and frame structures destroyed with foundation. Rails bent.
11 - *Extreme*	Few, if any masonry structures remain standing. Bridges destroyed. Rails bent greatly.
12 - *Cataclysmic*	Total destruction – everything is destroyed. Lines of sigh and level distorted. Objects thrown into air. The ground moves in waves or ripples. Large amounts of rock move position. Landscape altered, or levelled by several meters. In some cases, even the routes of rivers are changed.

Table 5. Values of I_{MCS} for different Limit States

	URM-1	URM-2	URM-3
DLS	6	7	8
ULS	7	8	9
CLS	8	9	10

7. Comparison With Ems98

Fragility curves obtained with the hybrid method have been compared with those empirical based on *EMS98* scale. Some researches adopted such scale to derive empirical fragility curves for Italian *URM* buildings typologies (Lagomarinso and Giovinazzi 2006, Del Gaudio et al. 2019, Rosti et al. 2020).

EMS98, useable at the European level, classifies the masonry buildings in seven different typologies (mainly differentiated as a function of masonry type) and to each of them associates a vulnerability class varying from *A* to *F* (Fig. 13). Moreover, each typology is susceptible of a *DS*, from *DS1* to *DS5*, as illustrated in Tab. 6.

Fragility curves developed by Lagomasino and Cattari (2014) - in turns derived from the macroseismic approach presented in Lagomarsino and Giovinazzi (2006) - have been considered for comparison purposes. Based on *EMS98*, they developed a multi-damage fragility model that for each vulnerability class (from *A* to *F*) define five fragility curves as a function of the Damage States.

To make this comparison, an analogy between the vulnerability classes of *EMS98* with respect to those defined in this paper has been established. Such correspondence is reported in Fig. 13: vulnerability class *A* of the *EMS98* (which represents the highest degree of vulnerability) corresponds to *URM-1*, vulnerability class *B* to *URM-2* and vulnerability class *C* to *URM-3*. As regards *URM-4* and *URM-5*, any correspondence can be defined, but at most they could be assimilated to class *C* and *A*, respectively.

This analogy finds its justification in the description of building classes reported in the *EMS98* document. In fact, for 'rubble stone, fieldstone' (vulnerability class A) it clarifies that are '*traditional constructions provided of very low seismic resistance, floors are typical of wood and no provide horizontal stiffening*'. This description corresponds to that provided for *URM-1*.

As regards 'simple stone' masonry (vulnerability class *B*) is specified that '*these hewn stone are arranged in the constructions to improve the strength of the structure, e.g. using large stone to tie in the walls at the corner*'. Despite that ties are not explicitly mentioned, it is reasonable that these provisions are aimed to encourage an in-plane behaviour of the walls. Thus, class *B* has been considered coincident with *URM-2*.

As regards 'unreinforced brick with reinforced concrete floors' (vulnerability class *C*), *EMS98* clarifies that the '*walls are connected and tied together with a rigid floor slab with ring beams, a box-like system is* *created which effectively reduces the risk of out-of-plane collapse of the walls, or the separation of drift of intersecting perpendicular walls'.* It is evident that such description coincides with that provided for *URM-3*.

As above-specified, fragility curves proposed in this paper are referred to *ULS* only: by analogy it coincides with the *DS4* defined by *EMS98*.

Table 6. Damage States provided by *EMS98*

Damage level	*Damage description*	*Type of damage*
DS1	*Negligible to slight damage*: no structural damage, slight non-structural damage (hair-line cracks in few walls, falls of small pieces of plaster)	
DS2	*Moderate damage*: slight structural damage, moderate non-structural damage (cracks in many walls, fall of fairly pieces of plaster, partial collapse of chimneys)	
DS3	*Substantial to heavy damage*: moderate structural damage, heavy non-structural damage (large and extensive cracks in most walls, roof tiles detach, failure of individual non-structural elements)	
DS4	*Very heavy damage*: heavy structural damage, very heavy non-structural damage (serious failure of walls, partial structural failure of roofs and floors)	
DS5	*Destruction*: very heavy structural damage (total or near total collapse)	

Fig. 14 compares the curves relative to the classes *A*, *B* and *C* obtained adopting logarithmic mean (m) and standard deviations (b) relative to the Damage State *DS4* (dashed lines) defined in Lagomarsino and Cattari (2014) with the average fragility curves relative to *URM-1*, *URM-2* and *URM-3* (continuous line), respectively.

Comparisons show that *a*) the slope of the fragility curves defined in this paper are greater than those of the macroseismic approach; *b*) the values of *PGA* at 50% of probability are best quantified, especially between *URM-2* and the vulnerability class B and between *URM-3* and vulnerability class *C*. Instead, a greater dispersion of *URM-1* with respect to the vulnerability class *A* resulted. A comparison among the values of m and b with respect to those found in Lagomarsino and Cattari (2014) and in Donà et al. (2020) is reported in Tab. 7.

Concerning the point *a*), the different slopes between the curves relative to the vulnerability classes *A*, *B* and *C* and those proposed in the present paper are due to the values of b. In fact, despite that the numerical values of b vary slightly with respect to that provided in Lagomasino and Cattari (2014) (as well as for Donà et al. 2020), they induce significant variation of slopes. This probably depends on the fact that the *EMS98* classifies the buildings as a function of materials and type of horizontal and vertical structures only, while the proposed classification takes also into account the seismic performance of the constructions. Then, in the latter case, it is reasonable that the structural response of the buildings is more homogeneous and characterized by lower values of b.

With respect to empirical-based approaches, different values of m and b resulted in the hybrid method are imputable to the cautionary nature of the methods used to assess the seismic capacity of masonry buildings. In fact, to cover uncertainties, a series of coefficients (such as safety factors of materials, confidence factor, knowledge level, behaviour factor, etc.), less or more correspondent to the real situations, are suggested by the Codes for evaluating the seismic capacity (i.e., the *PGA*). Obviously, in the case of empirical methods such coefficients are not considered, because based on a direct measure of the real observed damaging. By contrast, it should be also considered that the empirical approaches rely on the subjective judgement (and opinion) of the detector, which often affect the results also significantly.

Tab. 7. Comparison among logarithmic mean and standard deviation with literature values relative to Damage State DS4

Structural typology	*Equivalence with EMS98*	*Present paper*		*Lagomarsino and Cattari (2014)*		*Donà et al. (2020)*	
		m	b	m	b	m	b
URM-1	Class A	4.183	0.307	1.943	0.533	3.430	0.773
URM-2	Class B	4.784	0.223	3.209	0.538	n.a.*	n.a. *
URM-3	Class C	5.044	0.148	5.305	0.541	6.520	0.795

*n.a.=not available

8. Conclusions

A hybrid seismic fragility model for large-scale seismic vulnerability assessment of residential Italian masonry building stock has been proposed in this paper. The method combines the observational expert-judgment and mechanical approaches to derive typological fragility curves.

Based on observational expert-judgment, five typological classes of masonry buildings representative of the Italian *URM* constructions have been defined. Classification focuses on a strict correlation between age of construction, structural typology and observed seismic behaviour and damaging after earthquakes. These three parameters contribute together to define the *structural behaviour* of the typology, considered as the real discriminant of the subdivision in structural-typological classes.

Contrary to other literature classifications, that proposed is not based on the statistical processing of damage data derived from post-earthquake surveys. It is the result of the authors' experience developed in-field after the most severe earthquakes occurred in Italy in the last forty years and in academia.

The mechanical approach, instead, allowed to derive typological fragility curves separately for each typological class elaborated on the ULS damage state. Results of numerical analyses have been collected and elaborated to derive seismic Intensity Measures, in this study the Peak-Ground Acceleration (*PGA*) bearable by each buildings class at Ultimate Limit State.

Three different curves have been developed - each of them obtained considering as *IM* the mean, maximum and minimum value of *PGA*s - allowing for a more complete representation of the fragility. Such variability takes into account the different structural features and constructional details that changes as a function of the geographic area (also for the same typological class).

To represent the severity of an earthquake as a function of damage level inflicted to the buildings for increasing earthquake intensity, fragility curves in terms of Mercalli-Cancani-Sieberg macroseismic scale have been also elaborated.

The obtained fragility curves, in terms of both PGA and I_{MCS}, reflect the real vulnerability and post-seismic damage scenarios observed in the small Italian urban areas hit by severe earthquakes. Ancient Buildings (*URM-1*) have the highest vulnerability and are exposed to a high damaging also for low/medium-intensity earthquakes. While Improved-Ancient Buildings (*URM-2*) strengthened also with light local interventions or Modern Masonry Buildings (*URM-3*) can resist to medium/high-intensity earthquakes effectively.

The hybrid method-based fragility curves have been also compared with those empirical derived according to the *EMS98* scale. Comparisons show that mean values of *PGA* at 50% of probability of exceedance are comparable, while the slope of the hybrid curve is greater than those empirical. Such comparison highlighted that differences between the hybrid and macroseismic approaches are justified (and almost unavoidable) due to the approximation inherent in the method adopted to derive values of *PGA* within the mechanical method.

Declarations

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Figures

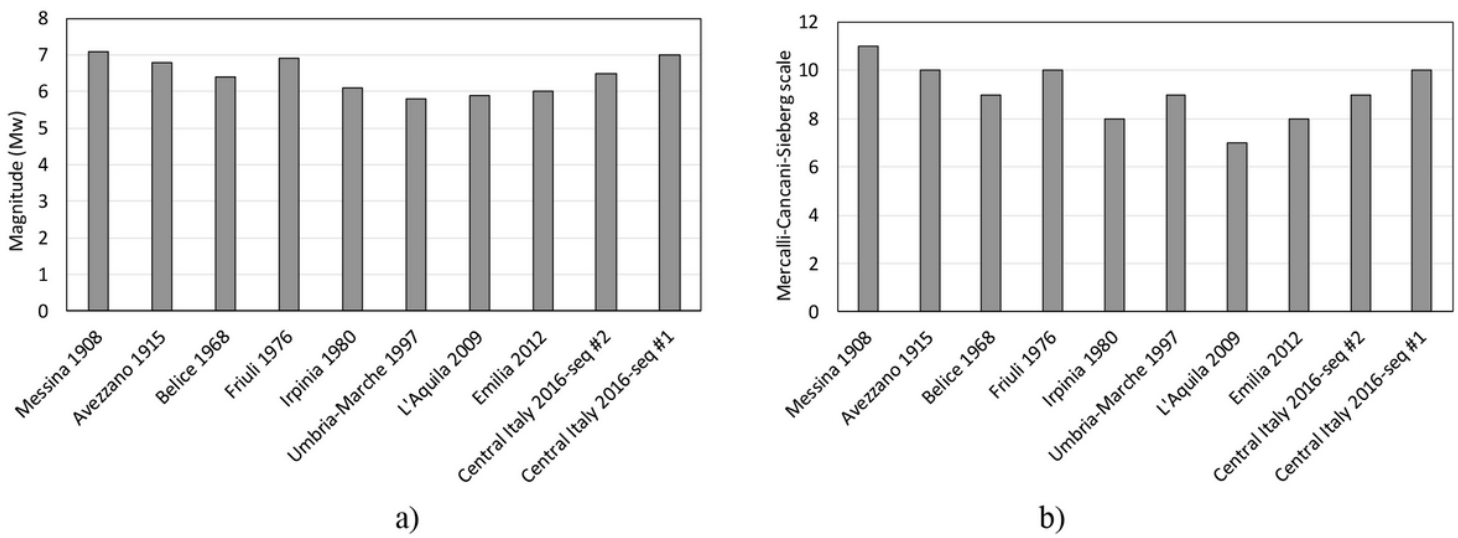

Figure 1

Reconnaissance of the most severe Italian earthquakes of the 20th century: a) Magnitude, b) MCS scale

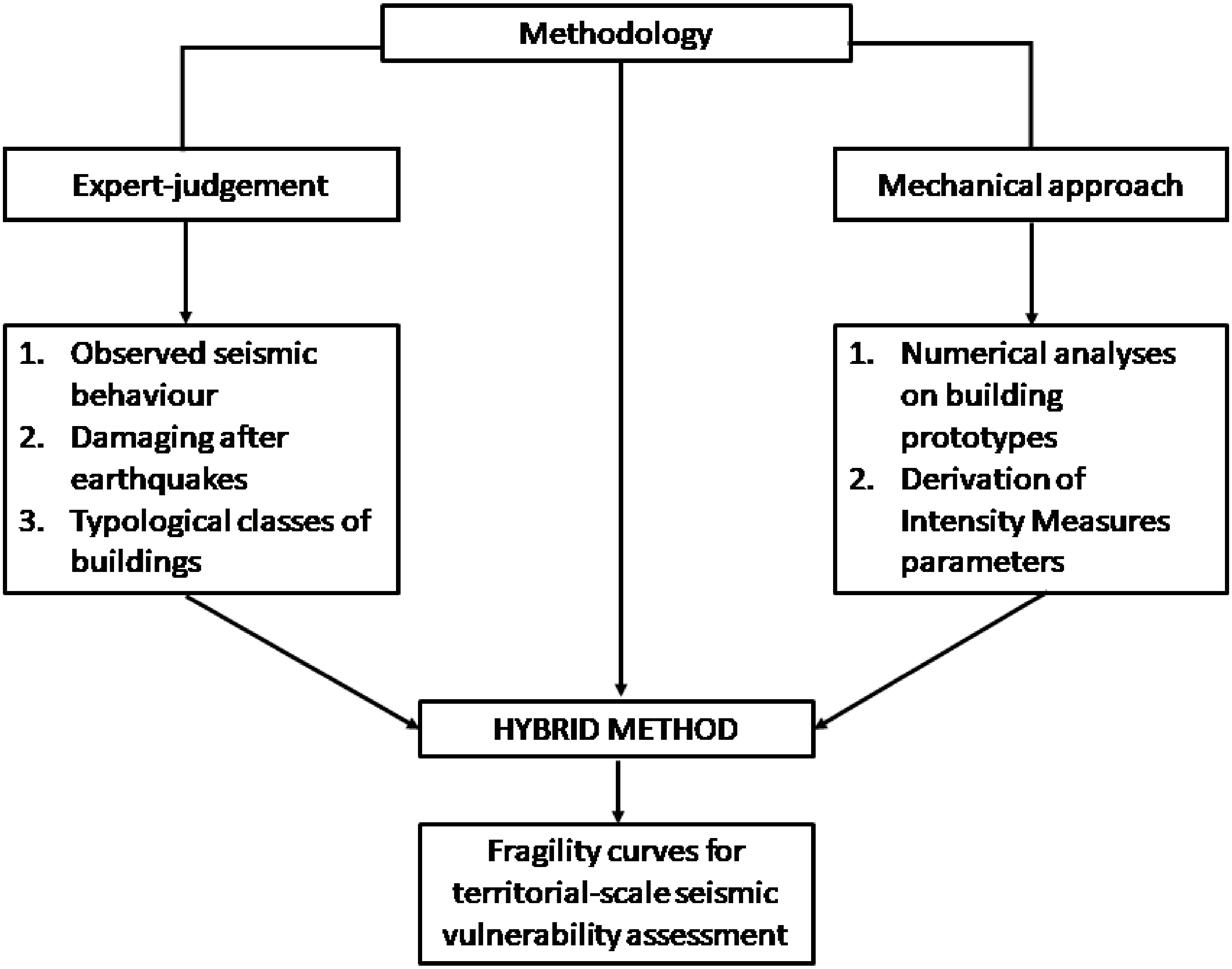

Figure 2

Conceptual map of the proposed methodology

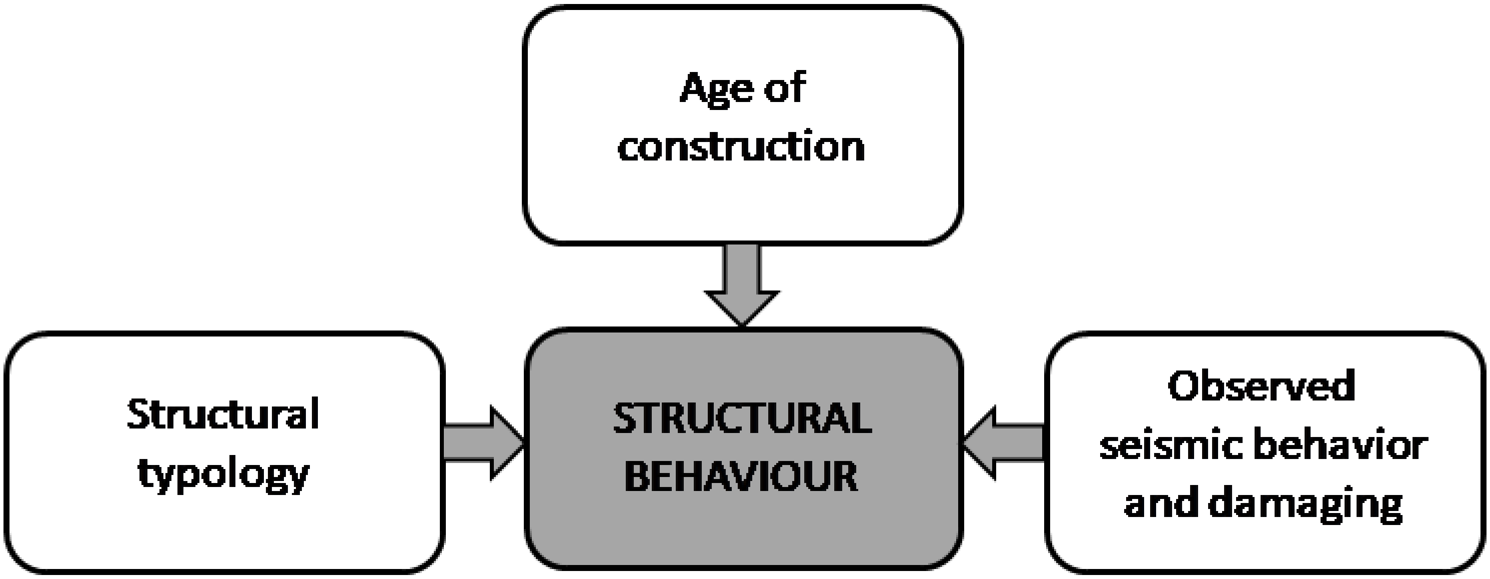

Figure 3

Correlation among the elements which define the structural-typological classification

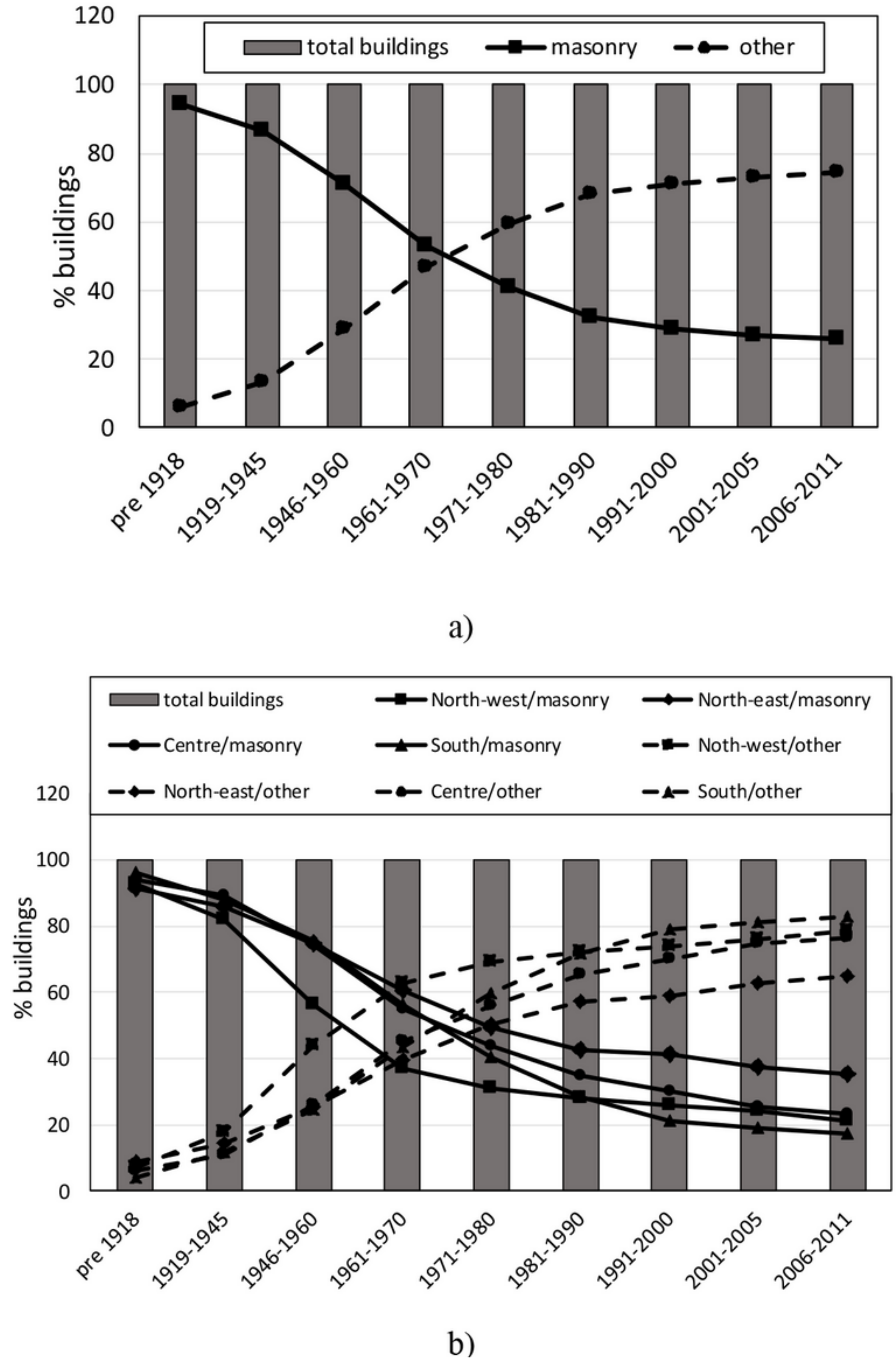

Figure 4

Buildings percentage in Italy from ISTAT database: a) total percentage in Italy, b) percentage divided by macro-Regions

a) b)

Figure 5

Ancient Buildings (URM-1): a) building with masonry vaults damaged from 2009 earthquake in L’Aquila (Abruzzi Region), b) building with wooden floors damaged from 2016-17 Central Italy earthquake in Amatrice (Lazio Region)

a) b)

Figure 6

Improved Ancient Building (URM-2): a) building damaged from 2009 earthquake in L’Aquila (Abruzzi Region), b) building damaged from 2016-17 Central Italy earthquake in Amatrice (Lazio Region)

a) b)

Figure 7

Modern Buildings (URM-3): a) building damaged from 2009 earthquake in L'Aquila (Abruzzi region), b) building damaged from 2016-17 Central Italy earthquake in San Severino Marche (Marche Region)

a) b)

Figure 8

Semi-Modern Building (URM-4) located in Naples: a) external side view, b) detail of r.c. ring beam

a) b) c)

Figure 9

No Code-Conforming Building (URM-5) damaged by 2012 Emilia Romagna earthquake and located in Mirandola: a) external side view, b) cracks which cross the inter-story level, c) inside horizontal crack due the absence of wall-to-floor connections

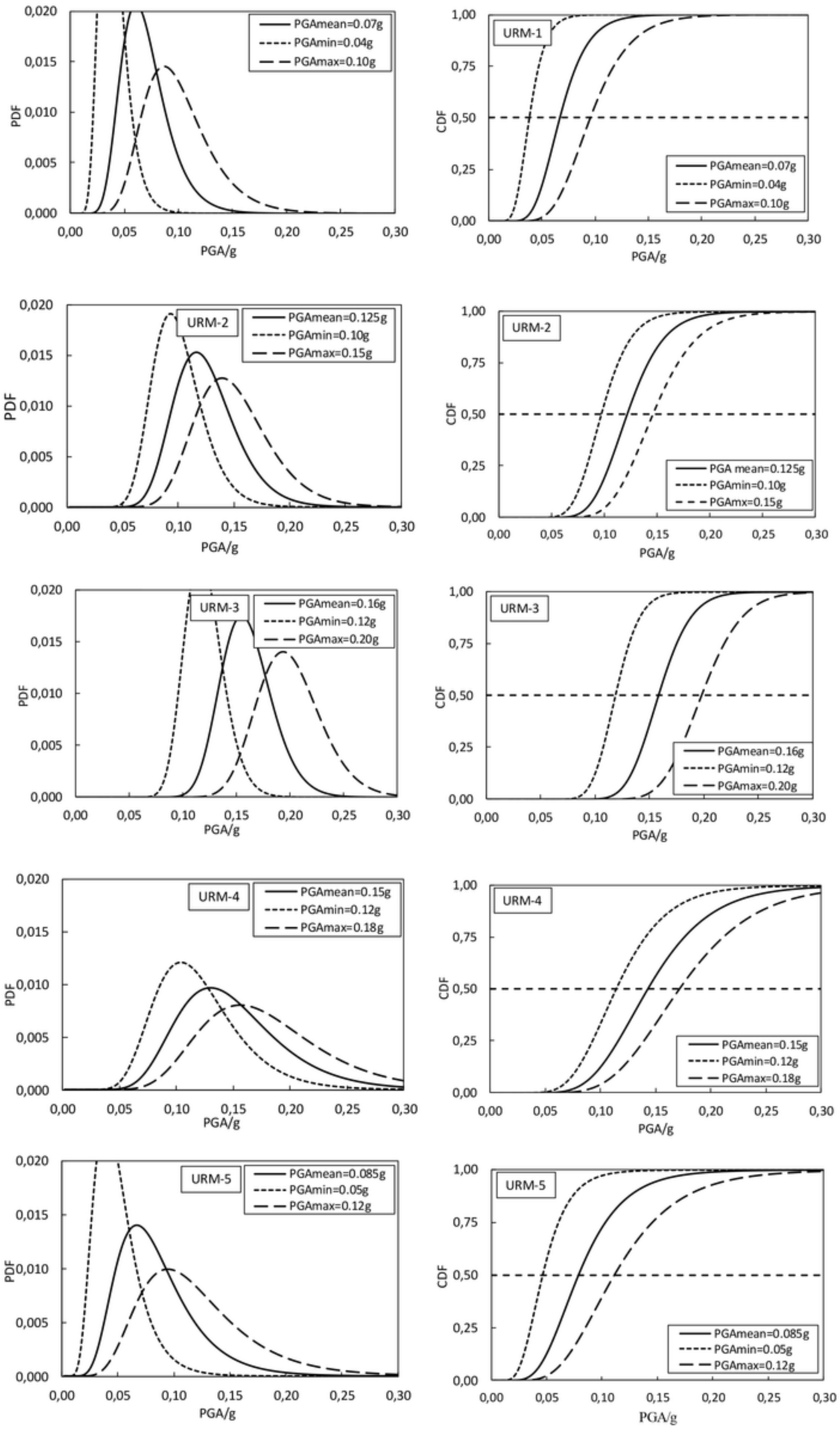

Figure 10

Probability and Cumulative density functions for the five building classes

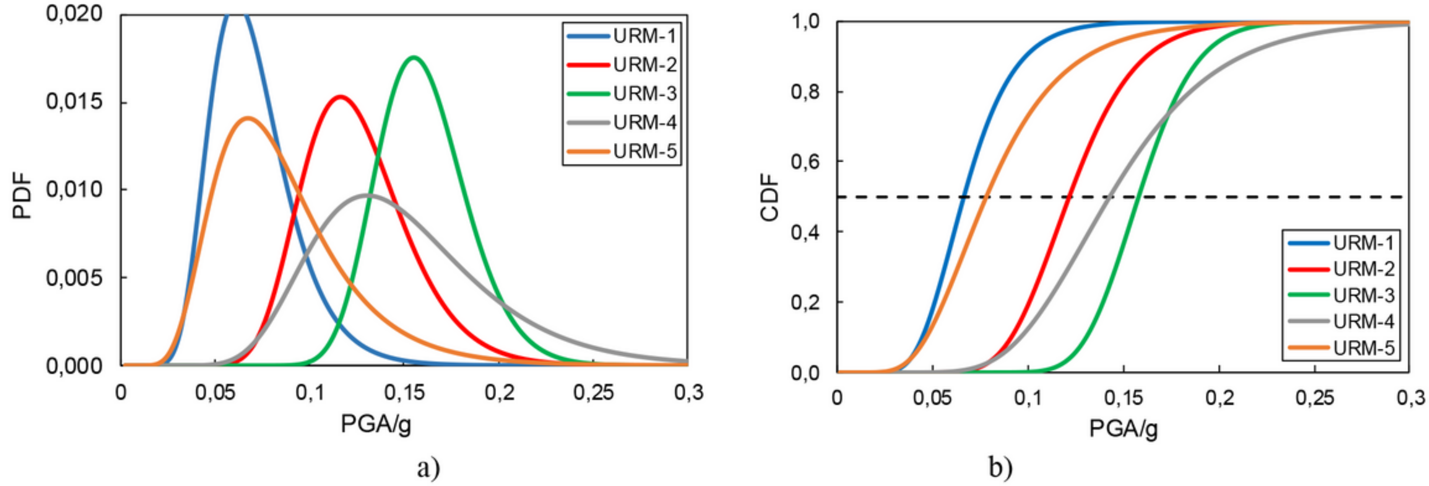

Figure 11

Comparison among a) probability and b) cumulative density functions for the five building's classes

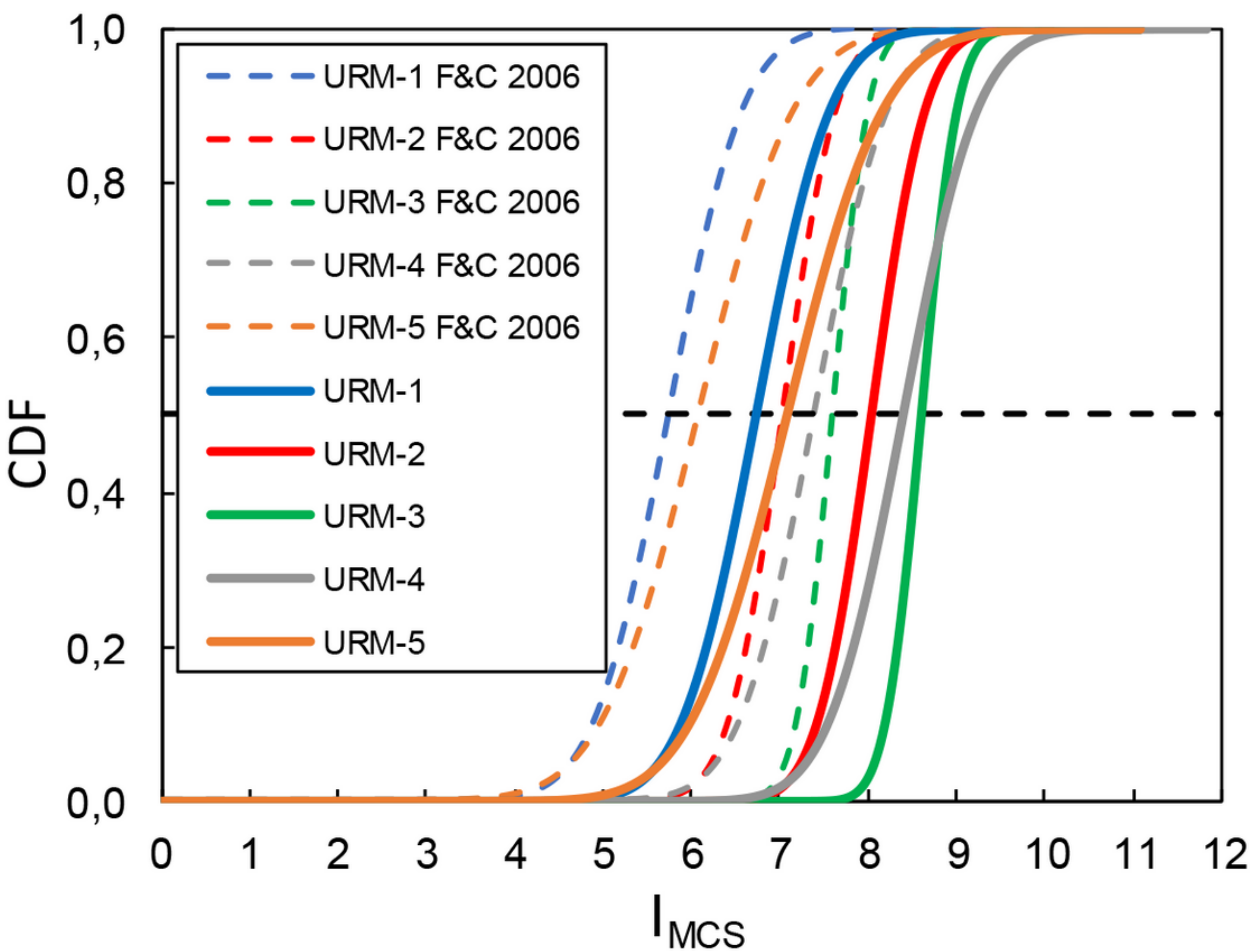

Figure 12

Fragility curves in terms of MCS scale

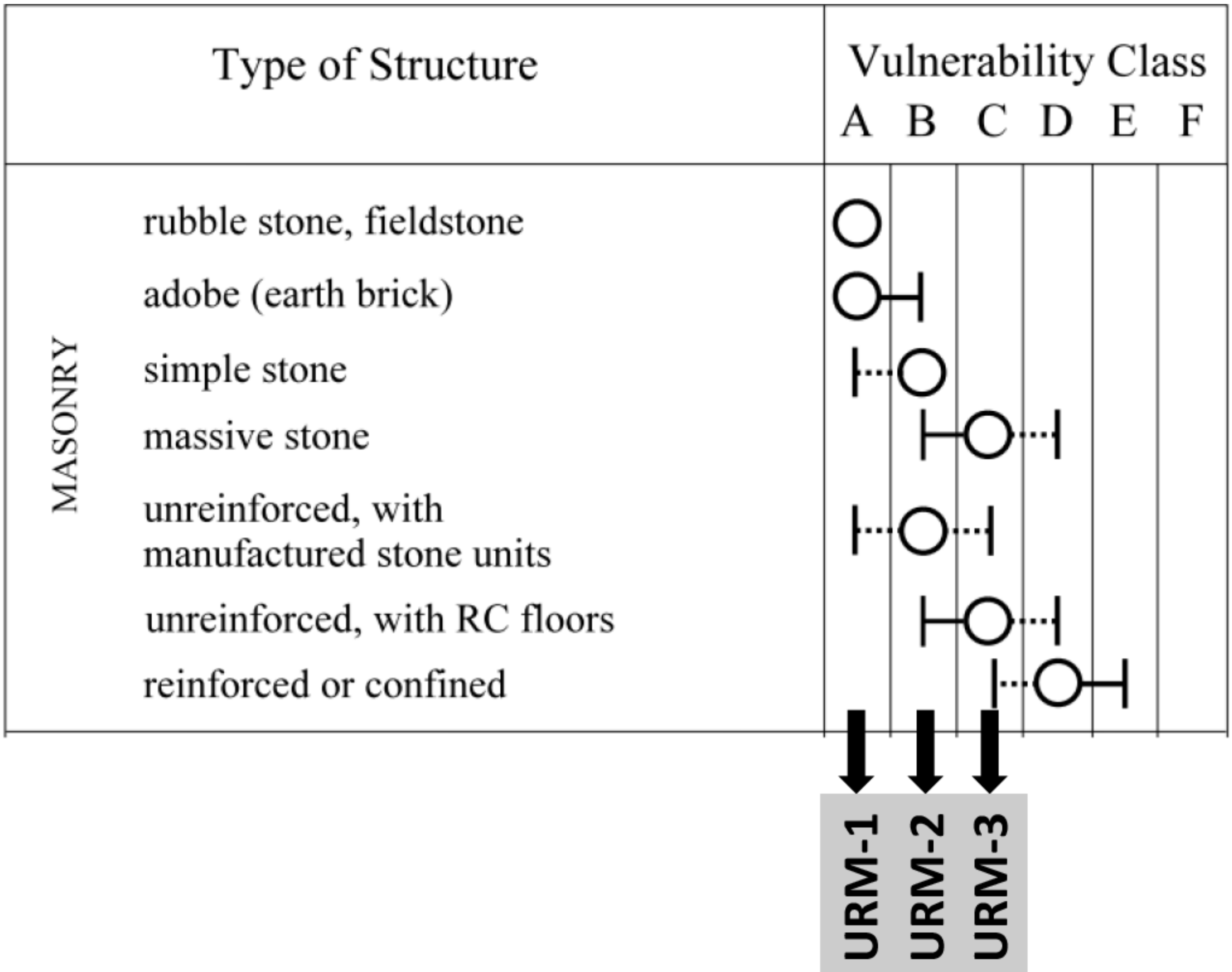

Figure 13

Correspondence between vulnerability classes of EMS98 and proposed classification

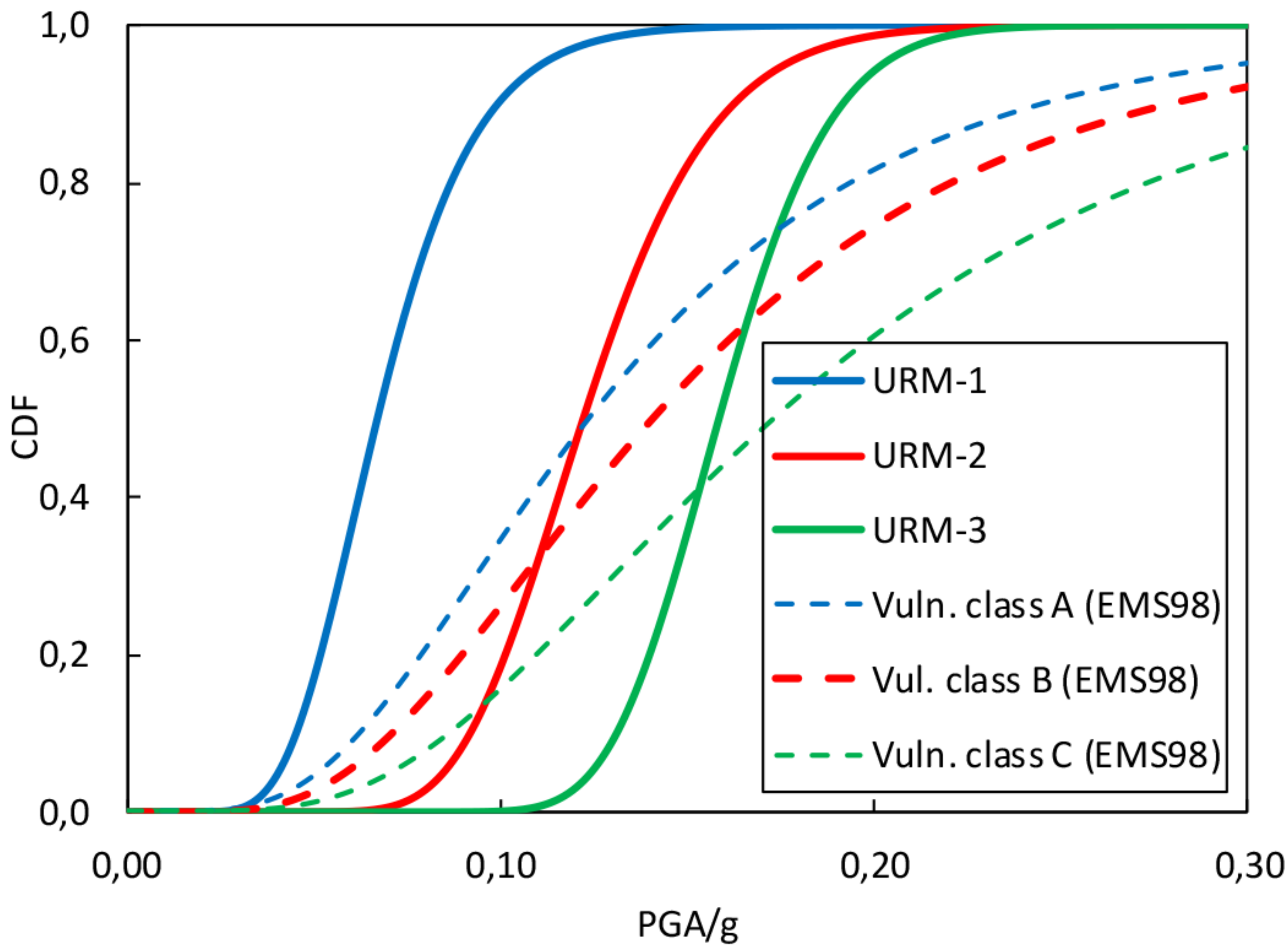

Figure 14

Comparison between EMS98 (DS4) and the proposed fragility curves.

Supplementary Files

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- AppendixTable.docx