



Seismic vulnerability assessment of minor Italian urban centres: development of urban fragility curves

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Abstract

This paper presents a novel hybrid-based methodology devoted to develop urban fragility curves and damage probability matrices to predict likelihood seismic damage scenarios for small and medium Italian urban centres, considering URM buildings only. The concept of urban fragility curve consists of a single curve mean-representative of the seismic fragility of an entire area accounting for the combinations of building classes and their percentage, then they differ from those typological. The methodology has been developed with reference to Rocca di Mezzo, a small Italian urban centre located in the central Apennine area, Italy. Based on CarTiS inventory, building classes have been firstly recognized and urban fragility curves, representative for damage scenarios at Ultimate Limit State, developed. To predict damage scenarios from low to high-intensity earthquakes, an approach to define multi-damage urban fragility curves and damage probability matrices has been also presented. To this aim, a damage scale suffered by building classes has been defined by converting the final outcomes of the AeDES form (used in Italy for post-earthquake surveys) in the damage levels provided by the European Macroseismic Scale (EMS98). Data coming from urban fragility curves have been compared with the actual damage scenario recorded in Rocca di Mezzo after the 2009 L'Aquila's earthquake, in terms of both peak-ground acceleration and Mecalli-Cancani-Sieberg scale. The achieved results showed a good accordance between theoretical predictions and actual damage scenarios, coherent also with the damage scenarios occurred in other Italian historical centres hit by severe earthquakes over the years. Thus, the methodology can provide a first important indicator to support the development of emergently plans devoted to identify priority of interventions in such areas particularly vulnerable with respect to others.

Keywords Urban fragility curves · Hybrid method · Historical centres · URM buildings · Multi-damage fragility curves · Damage scenarios · DPM

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1 Introduction

The prediction of the seismic risk scenarios for medium and small historical centres represents a fundamental tool in Italy to support national seismic prevention programs (Dolce et al. 2021). Italy is recognized as one of the European Nations mostly exposed to seismic risk. This is mainly due to the high seismic hazard which characterizes the entire Apennine ridge that crosses the Italy from North-center to South-center (for about 1200 km) and due to the presence of medium–high vulnerable constructions (Calderoni et al. 2011; Formisano and Massimilla 2018; Sorrentino et al. 2019; Sandoli et al. 2020). Minor historical centres are particularly prone to high seismic vulnerability because composed by poorly detailed masonry buildings made with poor masonry quality (D’Ayala and Panagoni 2011; Calderoni et al. 2016; Brando et al. 2020).

The development of fragility models aiming to predict the seismic vulnerability scenarios for urban areas are crucial to support post-earthquake emergency phases through real time-time loss estimations, to plan mitigation strategies and to define priority of interventions on existing buildings oriented to mitigate their seismic vulnerability and economic losses. This is a particular issue felt in all those Regions exposed to high seismic risk all over the world (Altug Erberik 2007; Lovon et al. 2018; Biglari and Formisano 2020).

In the perspective of this, numerous methodologies devoted to large-scale seismic vulnerability assessment have been developed by researchers in the last years, or are still under studying. The final goal of each method consists in developing fragility curves and probable seismic damage scenarios referred to urban, sub-regional or regional scale areas, accounting for characteristics of the existing building stock.

Methods for seismic assessment are basically classified as empirical, mechanical (or analytical), expert-judgement and hybrid. Empirical methods are based on statistical treatments of data coming from post-earthquake survey considering a significant buildings population, starting from which damage probability matrices (DPMs) and fragility curves representative of building typologies or of an entire area are derived (Zuccaro and Cacace 2015). Mechanical approaches rely on a lower number of data derived from numerical analyses conducted on real or simulated buildings prototypes and statistically processed to derive the fragility curves (Donà et al. 2020; Belliazzi et al. 2021). Expert-judgement approaches provide fragility curves based upon the experience of a team of experts which are asked to estimate the structural behaviour and the average damage level for various building classes. The damage estimates are then fitted by means of probability functions to obtain fragility curves (ATC 1985; Rota et al. 2008). Finally, hybrid methods combine two of the above-mentioned approaches to develop fragility models (Calvi et al. 2006; Kappos et al. 2006). An extensive state-of-art on pros and cons of the different methodologies adopted by researchers are discussed in Calvi et al. (2006) or in Kassem et al. (2020).

Numerous valuable models devoted to derive fragility curves for Italian masonry building classes with territorial-scale valence have been presented in literature. Empirical approaches are those mainly adopted since from the past (Braga et al. 1982; Di Pasquale et al. 2005; Rota et al. 2008). Recently, Del Gaudio et al. 2019 defined empirical fragility curves for Italian masonry buildings after the 2009 L’Aquila’s earthquake; they identified twenty classes of masonry building and defined damage scenarios for a large area around L’Aquila city. Rosti et al. (2020a, b) focused on damage classification and derivation of DMPs from L’Aquila post-earthquake survey (based on the first level AeDES survey form, used in Italy for post-earthquake damage surveys for ordinary buildings). They highlighted the effectiveness of different methodology used to assign a damage level to inspected

buildings. Brando et al. (2021) presented a novel empirical-based predictive model for the rapid seismic vulnerability assessment with reference to a little town located in the Marche Region (central Italy). They explored the building inventory given by the CarTiS database (Zuccaro et al. 2015) and defined both multi-damage fragility curves and damage scenarios for the considered urban area.

With regards to mechanical and hybrid methods, an analytical approach to derive fragility curves based on nonlinear stochastic analyses of masonry building prototypes has been proposed in Rota et al. (2008), they involved Monte Carlo simulations to generate input variables (e.g., material properties) and nonlinear static analyses to define the probability distributions. Donà et al. (2020) classified the masonry buildings in ten different macro-typologies as a function of the age of construction and the number of storey, based on the ISTAT (Italian National Institute of Statistic) database. The sampled buildings have been processed through the software *Vulnus_4.0* which provides, on a mechanic base, the fragility curves according to the European Macroseismic Scale EMS98 (Valluzzi 2009) Finally, Cima et al. (2021) presented a mechanics-based approach for evaluating fragility curve for macro-categories of masonry buildings prone to out-of- plane mechanisms, representative for the central Italy small urban centres.

Lagomarsino and Giovinazzi (2006) presented one of the first hybrid vulnerability models which combines the macroseismic method (based on expert elicitation) with the mechanical approach: the vulnerability of a group of buildings is defined by means of vulnerability indices, from which expertise-based fragility curves are analytically obtained. Such method has been recently up-dated in Lagomarsino et al. 2021, where damage data are derived from the Da.D.O database (Database of Observed Damage) which collects observed damage on buildings after the main Italian earthquakes during the last forty years (Dolce et al. 2019). Conversely, a hybrid approach based on expert-judgement and mechanical contributions has been presented in Sandoli et al. (2021) where typological fragility curves for five classes of masonry buildings, representative of the recurrent Italian typologies, have been derived.

1.1 Scope of the research

Literature overview highlighted as the majority of the papers focused on the definition of *typological* fragility curves, i.e. devoted to represent the fragility of single building classes scattered throughout the national territory. On the contrary, few works extended their results aimed at developing *urban* fragility curves, the latter intended as a single ‘mean-representative’ curve descriptive of the seismic fragility of an entire urban area depending on both building classes and their percentage (Del Gaudio et al. 2019; Brando et al 2021).

This paper presents a novel hybrid-based methodology devoted to derive urban fragility curves and damage scenarios for typical minor Italian historical centers. The method takes inspiration from the results presented in Sandoli et al. (2021), where five masonry building classes representative of typical Italian URM building stock and the relative typological fragility curves at ULS have been elaborated combining expert-judgement with mechanical approach. As first step, with reference to the small urban centre of Rocca di Mezzo (placed in the district of L’Aquila—Abruzzi region), the CarTiS inventory has been explored to recognize the masonry building types and to associate them with the five building classes proposed in Sandoli et al. (2021). Based on the identified classes, a methodology to transform ‘typological’ into ‘urban’ fragility curve, oriented to predict the likelihood damage scenario at Ultimate Limit State (ULS), has been developed.

In the second part of the research, urban multi-damage fragility curves and DPMs have been also developed. To this aim, data provided by the AeDES survey forms combined with the building classes identified through the CarTiS database have been processed and a new damage scale proposed. The latter has been obtained by converting the usability outcomes provided by AeDES in Damage States (DS) given by EMS98 (Grünthal 1998).

Data coming from urban fragility curves and DPMs have been compared with damages occurred in the area under study (located few km away from L'Aquila) caused by the 2009 L'Aquila's earthquake, providing satisfactory results.

2 Research background

A reconnaissance of the buildings inventory is necessary for developing urban fragility curves for the area under study. In this paper, both masonry building classes and typological fragility curves recently proposed in Sandoli et al. (2021) have been considered as a reference, thus it is important to recall the main aspects and achieved results.

It is a hybrid-based method which combines expert-judgement with mechanical approach, oriented to large-scale seismic vulnerability assessment. The first approach provided a structural-typological classification of the ordinary unreinforced masonry (URM) buildings, grouped in five different macro-classes representative of the Italian building stock; the second gave the statistical variables (e.g., mean and standard deviation of the chosen Intensity Measure) necessary for developing typological fragility curves. Such variables were derived processing a consistent number of linear and nonlinear structural analyses on masonry building prototypes, in part conducted by the authors and in part found literature. In particular, data coming from linear and nonlinear kinematic analyses have been processed for the building classes prone to out-of-plane failure mechanisms, while nonlinear static/dynamic analyses for the those dominated by an in-plane behavior of the walls.

Buildings classes are the results of the combination of three different factors: age of construction, structural typology (type and arrangement of horizontal and vertical structures, structural details) and observed seismic behavior and damaging. Together, such factors identify the 'global seismic behavior' of the class, which represents the key aspect to differentiate the URM buildings in macro-typologies.

The main features of the five building classes, indicated with the acronym from URM-1 to URM-5, are summarized in Table 1. Instead, the corresponding typological fragility curves, obtained through a lognormal Cumulative Density Function (CDF), are indicated in Fig. 1. As Intensity Measure (IM) it has been used the maximum Peak-Ground Acceleration (PGA) bearable by each building class at Ultimate Limit State (ULS), whose values of PGA mean and its standard deviations referred to the normal distribution are reported in the reference paper. Conversely, the lognormal mean (μ) and standard deviation (β) of the $IM=PGA$ used for defining the lognormal distribution are reported in Table 2. In such table, three values of μ —Minimum, Mean and Maximum—are reported, they take into account for uncertainties related to numerical evaluations, number of storey greater than three, material properties, presence of aggregates. In such a way, a range of fragility for each building class has been defined, resulting representative for identifying seismic damage scenarios at large-scale. In fact, three fragility curves for each building class were defined in Sandoli et al. (2021) but only those relative to the Mean values of μ for each typology are reported in Fig. 1.

Table 1 Summary of the main characteristics of the building classes defined in Sandoli et al. (2021)

Building class	Age of construction	Structural typology	Seismic behavior/damaging
URM-1 (Ancient buildings)	Before 1937 in non-seismic areas or before the year of the introduction of specific seismic codes for zones hit by earthquake from 1908 to 1937	Masonry walls without seismic devices devoted to prevent out-of-plane mechanisms of the façade walls. In-plane deformable floors	Out-of-plane mechanisms of the façade walls
URM-2 (Improved ancient buildings)	Before 1937 in non-seismic areas or before the year of introduction of specific seismic codes for zones hit by earthquake from 1908 to 1937	Masonry walls strengthened to prevent out-of-plane mechanisms of the façade walls. In-plane deformable floors	In-plane mechanisms of the masonry walls. Rarely local out-of-plane collapses of masonry walls portions
URM-3 (Modern buildings)	After 1937 in the non-seismic zones. Before 1937 for those areas declared as seismic from 1908 to 1937	Masonry walls interrupted at each inter-story level by r.c. ring beams connected to the floors. In-plane rigid or semi-rigid floors	In-plane mechanisms of the masonry walls
URM-4 (Semi-modern buildings)	Before 1937, but after the year of introduction of specific codes for the zones hit by earthquakes from 1908 to 1937 or before 1937 in the non-seismic area	Masonry walls with r.c. or steel rings not well connected to the floors. In-plane rigid or semi-rigid floors	In-plane mechanisms of the masonry walls. Rarely local out-of-plane collapses of masonry walls portions
URM-5 (No code-conforming buildings)	After 1937 in non-seismic zones or before 1937 but after the year of introduction of the corresponding codes for the zones affected by earthquakes from 1908 to 1937	Masonry walls not effectively connected to the floors because of the absence of specific devices (r.c. or steel rings, steel ties). In-plane rigid or semi-rigid floors	Local or global out-of-plane mechanisms of the façade walls

Fig. 1 Typical fragility curves for Italian URM building classes (from Sandoli et al. 2021)

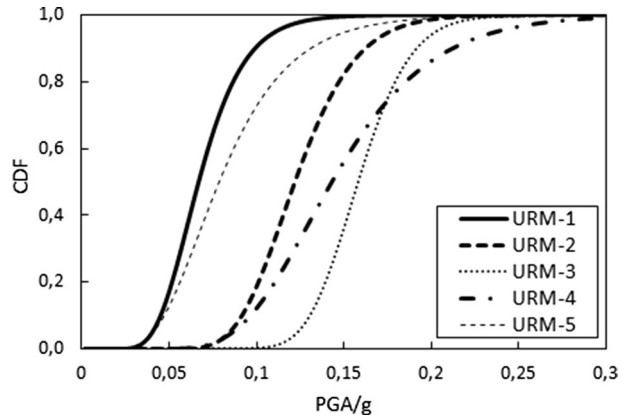


Table 2 Values of logarithmic mean (μ) and standard deviation (β) of the lognormal distribution (from Sandoli et al. 2021)

Build. class	Minimum (μ)	Mean (μ)	Maximum (μ)	St. deviation (β)
URM-1	3.622	4.182	4.583	0.307
URM-2	4.561	4.874	4.967	0.223
URM-3	4.757	5.044	5.268	0.148
URM-4	4.721	4.944	5.126	0.307
URM-5	3.813	4.343	4.688	0.398

It is important to recall that these fragility curves refer to a single DS, here identified with the ULS. This because the results of the numerical analyses available in literature generally refer to the maximum PGAs bearable by the buildings for the ULS. Contrariwise, values of PGAs representing the achievement of other Limit States (i.e., Damage or Collapse Limit State) are rarely provided, then they have been considered not statistically valid for the paper purposes. Nevertheless, to have a feedback in terms of EMS98, in the reference paper it has been highlighted that the achievement of the ULS corresponds to the damage state DS4 given by the EMS98.

The five building classes seems to be effective to represent the Italian URM building stock. They have been recently adopted in Cardinali et al. (2021) to derive fragility curves for masonry buildings aggregates. While, Cima et al. (2021) compared their fragility curves relative to Italian masonry building located in the Central Apennine area with our proposal, obtaining satisfactory results.

3 Description of the case study

Rocca di Mezzo is a small Italian centre located 20 km from L'Aquila, in the central Apennine area (Abruzzi region) (Fig. 2a). It has about 1400 citizens, with a territorial extension about of 90 km². In addition to the main municipality of Rocca di Mezzo (which gives the name to the entire town), it comprises other three sub-municipality named with Terranera, Rovere and Fonteavignone placed few kilometres of distance among them.

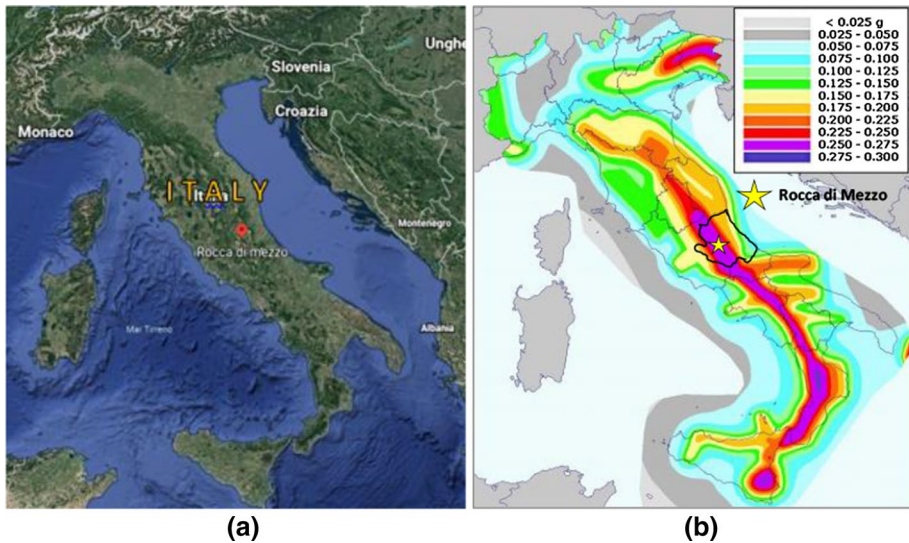


Fig. 2 **a** Map of Italy with location of Rocca di Mezzo (Source: Google Earth Pro), **b** Italian seismic hazard map in terms of peak-ground acceleration provided by IBC18 for a return period of 475 years (Source: INGV)

Rocca di Mezzo was hit by the 2009 L'Aquila's earthquake that caused significant damage to buildings. After this seismic event, it was planned a Reconstruction Plan aimed at the urban redeveloping the four sub-municipalities. Such plane, available on the web site of Rocca di Mezzo's municipality (www.comune.roccadimezzo.aq.it) and elaborated by a study group from the University of Rome 'La Sapienza', has been of particular importance in the present research to derive information concerning the building types (material, types of interventions. etc.), number of buildings, seismic hazard and damage scenario after the 2009 L'Aquila's earthquake.

3.1 Seismogenetic history

Due to presence of several active faults that have activated significant earthquakes during the centuries, the central Apennine area is recognized with a high seismic hazard (Cello et al. 1997). According to the current seismic hazard map provided by the Italian Building Code 2018 (IBC18) (Fig. 2b), a peak-ground acceleration $a_g = 0.26 g$ for a return period of 475 years (i.e., at ULS) is expected for the area of Rocca di Mezzo.

Figure 3 reports the chronological order of the seismic events with magnitude (M_w) greater than 5.0 occurred in a zone with a radius of 50 km around L'Aquila since the year 1345, including Rocca di Mezzo and its sub-municipalities. Particularly severe seismic events were those dated 1915 (Avezzano's earthquake— $M_w = 7.08$), one of the most disastrous occurred in Italy that caused about 30000 casualties, and 2009 (L'Aquila's earthquake— $M_w = 6.29$) that caused about 300 victims.

The effects of L'Aquila's earthquake are of particular interest for the research purposes, because data for elaborating the urban fragility curves and for assessing the seismic vulnerability of the entire centre of Rocca di Mezzo refer to this event. To this aim, the shake map

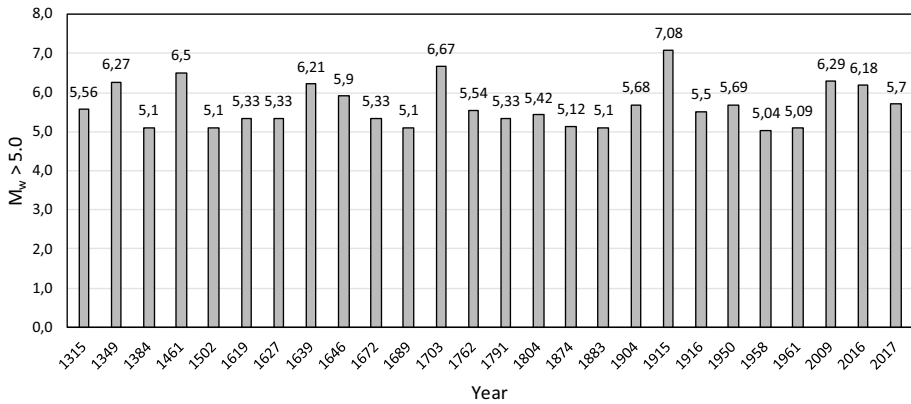


Fig. 3 Sequence of earthquakes with magnitude $M_w > 5.0$ for a zone with a radius of 50 km around L'Aquila (values referred to the epicenter)

provided by the INGV (National Institute of Geophysical and Volcanology), expressed in terms of MCS intensity scale (I_{MCS}) and relative to the 2009 earthquake, is shown in Fig. 4. The MCS intensity recorded for Rocca di Mezzo, Rovere and Fonteavignone resulted $I_{MCS} = 6.0$, and between 5.0–6.0 for Terranera. Instead, an I_{MCS} about 9–10 was recorded for the epicentral area around L'Aquila city.

With regards to the peak-ground accelerations a_g (on bed rock) that hit Rocca di Mezzo, all the maximum values recorded from 2nd to 21th century are summarized in Fig. 5.

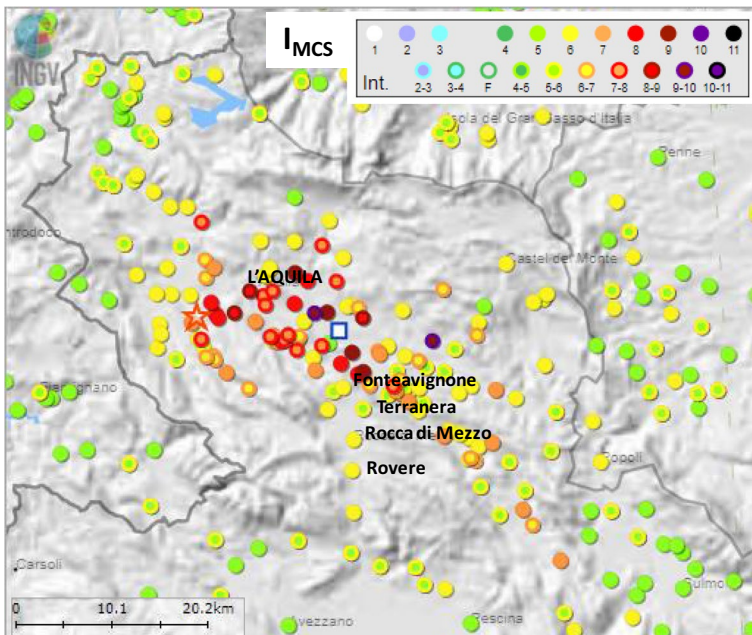


Fig. 4 Shake-map in term of MCS intensity after the 2009 L'Aquila's earthquakes (from INGV, Italy)

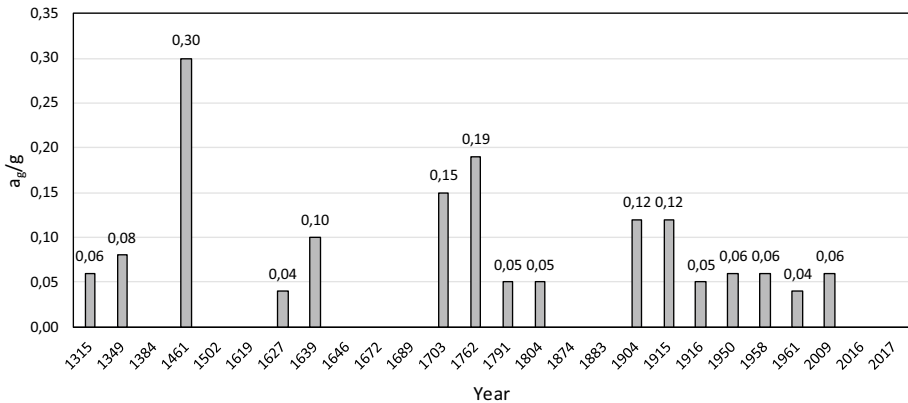


Fig. 5 Maximum peak-ground accelerations estimated for Rocca di Mezzo during the centuries

Such accelerations were provided by the elaboration reported in the Reconstruction Plan of Rocca di Mezzo, in turn obtained by adopting the formulation which relates I_{MCS} with a_g proposed by Decanini et al. (1995). As it can be observed, an acceleration $a_g = 0.06 g$ struck Rocca di Mezzo and its sub-municipalities (located at 20 km away from L'Aquila) following the 2009 L'Aquila's earthquake; for such an acceleration a return period equal to 37 years was estimated, which is representative of medium/low intensity seismic events.

3.2 Historical genesis and urban planning

Rocca di Mezzo is a Romanic town, mainly developed in the mediaeval age, that falls in the so called “*area delle neve*” (snow area). Its particular orographic position produced natural barriers that made difficult the communications with the other territories, relegating the city to a particular atavistic isolation allowing the development of rural housing.

During the centuries, the urban planning of the town has not changed in a significant way. The historical centre comprises from single to three-story URM buildings, in aggregate or isolated, made out with chaotic rubble stone masonry in poor quality mortar, as the majority of masonry buildings present in the neighborhoods of L'Aquila (Sandoli and Calderoni 2018). Conversely, few reinforced concrete buildings in the historical centre are included.

From an architectural point of view, a reconnaissance of the building types is reported in the Reconstruction Plan of Rocca di Mezzo, thanks to which it has been possible to recognize the morphological aspects of the constructions in terms of walls geometry (horizontal and vertical misalignment of openings in façades), mean distance among the walls, in plan walls' arrangements and percentage of buildings in aggregate or isolated.

Nevertheless, the authors performed a local survey 12 years after the L'Aquila's earthquakes. This was an opportunity for identifying more in detail the features of the building types concerning their morphology, geometry, materials and techniques of intervention. It has been noted a significant number of buildings not yet repaired since the seismic event of 2009 (Fig. 6), while others were repaired before 2009 due to the effects of previous earthquakes. According to the building classes recalled in the Table 1, Rocca di Mezzo's buildings can be categorized belonging to the classes URM-1 (ancient buildings) and URM-2 (improved ancient buildings): after the earthquakes, many masonry buildings originally belonging to the



Fig. 6 Typical URM masonry buildings in Rocca di Mezzo and in its sub-municipalities: **(a)** masonry buildings in Rocca di Mezzo damaged after 2009 L'Aquila earthquake, **(b)** masonry buildings repaired with horizontal steel ties in Rovere, **(c)** post-earthquake temporal safeguards applied to masonry buildings in Fonteavignone (photos date back 2021)

class URM-1 were strengthened by means of local interventions aimed at preventing the out-of-plane failure mechanisms of the facade walls, becoming of class URM-2. Other buildings, constructed ex-novo, are reinforced concrete structures.

Reconstruction Plane highlighted that few masonry buildings collapsed in Rocca di mezzo due to the effects of 2009 L'Aquila's earthquake. Some of them suffered a significant damaging resulting as unusable in the aftermath of the earthquake, especially in the sub-municipalities of Terranera and Fonteavignone (as better discussed in the following).

4 Methodology

In this section a methodology for developing urban fragility curves is presented. It is a hybrid approach combining expert-judgment with mechanical procedure. Through the expert-judgement, building types provided by CarTiS have been categorized within the five macro-classes defined in Table 1, while through the mechanical contribution all the statistical parameters (e.g., mean and standard deviation) necessary to develop the fragility functions for urban areas have been calibrated.

4.1 Recognition of the building's classes and their population

Different databanks for the reconnaissance of the structural features of the buildings located in the minor historical centres are available in Italy. A database widely used by researcher to develop large-scale seismic vulnerability methods is the ISTAT building inventory, which cover the entire national territory. It is a robust database providing the number of buildings and their constructional techniques (i.e. masonry, reinforced concrete or other) referred to specific time intervals. Despite that, the ISTAT database does not contain indications on damage surveys of the constructions following the most important Italian earthquakes. To fill this gap, other databases were developed over the years accounting for seismic damaging coming from post-earthquake inspections forms. As an example, the PLINIVS database released by the University of Naples Federico II includes data of about 240000 damaged buildings, collected after the major Italian earthquakes starting from 1980 Irpinia' earthquake (Zuccaro et al. 2021).

Recently, the database Da.D.O. (Observed Damage Database) has been introduced by the Italian Department of Civil Protection. It covers more than 332000 buildings, including data on both structural characteristics and seismic damage levels of the buildings surveyed following the most important Italian earthquakes (from 1976 Friuli's up to 2013 Garfagnana-Luigiana's earthquake) (Dolce et al. 2021).

In this paper, the building inventory provided by the CarTiS database for the municipality of Rocca di Mezzo has been explored. CarTiS is a research project promoted by Italian Department of Civil Protection in collaboration with ReLUIS (Italian Network of Academic Laboratories of Earthquake Engineering) whose main goal consists of collecting an inventory of the ordinary masonry buildings in Italy and implementing procedures for seismic risk assessment at regional, sub-regional or national scale (Zuccaro et al. 2015). Data are collected through an interview-bases survey to local technicians using the 'CarTiS form', uploaded on a devoted web-site application freely available for the researchers engaged in the research project. As a result, consistent information relative to the building's features included in a pre-defined urban area—in terms of age of constructions, types of vertical (i.e., masonry type) and horizontal structures, structural details and types of interventions—are provided. The extension of the reference urban area (or compartment) is defined by the detectors of the CarTiS form, as a function of census area defined by the ISTAT or of the building types and the municipality extension. Nowadays, the CarTiS database cover the 4–5% of the Italian municipalities and many researches are engaged in the research project, contributing to develop methodologies for territorial scale seismic risk analyses (Polese et al. 2020; Brando et al. 2021).

Concerning Rocca di Mezzo and its sub-municipalities, CarTiS defines 12 different urban compartments indicated from C01 to C12 (Fig. 7). The building typologies resulted



Fig. 7 Identification of the urban compartments provided by CarTiS database

for each compartment have been correlated with the five building classes presented in Table 1. In other terms, each building typology provided by CarTiS has been recognized as one among URM-1, URM-2, up to URM-5, depending on buildings' features and age of construction. The obtained data have been summarized by means of the histograms in Fig. 8: they indicate, for each urban compartment, the building's population in numerical and percentages terms subdivided by typological classes. To cover the total number of buildings, reinforced concrete constructions have been also included in the histograms despite that they have not been computed to define the fragility of Rocca di Mezzo.

A total number of 1226 masonry buildings resulted from the database, the great part of them belong to the classes URM-1 (751 blds) and URM-2 (475 blds), all falling back in the historical centres of the four sub-municipalities. Conversely, the number of reinforced concrete constructions is lower and mainly concentrated in the expansion urban zones reconstructed as a consequence of earthquakes occurred over the years.

4.2 Fragility function

The hybrid methodology to define the urban fragility curves herein presented is an advancement of that proposed for deriving typological fragility curves summarized in Sect. 2. For this purpose, the typological fragility functions have been particularized to a specific urban area or compartment by merging statistically (i) the buildings classes and (ii) the number of buildings for each class. The twelve urban compartments defined by CarTiS and listed in the previous section have been used as reference areas.

To process the collected data, different statistical distributions can be used. In this study the lognormal distribution has been employed, as in the majority of works focused on the definition of fragility curves (Rota et al. 2008; Del Gaudio et al. 2019; Cima et al. 2021). The lognormal Cumulative Density Function (CDF) which define the fragility function is reported in the following:

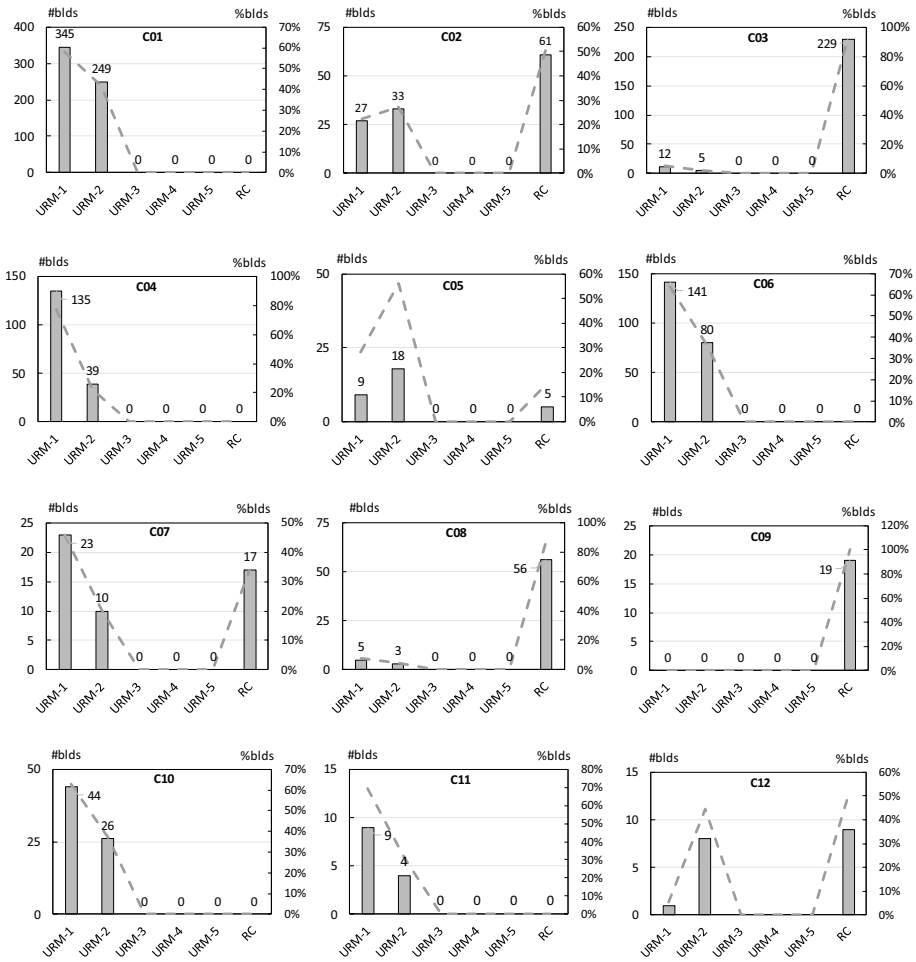


Fig. 8 Number and percentage of the building classes recognized through CarTiS database in the urban compartments of Rocca di Mezzo

$$CDF = F(X) = \int_0^X f(x)dx \tag{1}$$

where the term $f(x)$ represents the lognormal Probability Density Function (PDF) expressed as follows:

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

where im is the generic value of the chosen Intensity Measure (IM) parameter, while $\bar{\mu}$ and $\bar{\beta}$ are the median and the standard deviation of the distribution associated with a specific

DS. Note that, with reference to a single urban compartment, both $\bar{\mu}$ and $\bar{\beta}$ are not representative for a single building class (as in the case of typological fragility curves), but they have been calculated as weighted values with respect to the building percentages included in the considered compartment (divided by building classes). The mathematical formulations used for calculating $\bar{\mu}$ and $\bar{\beta}$ are reported in the following:

$$\bar{\mu} = \frac{\sum \mu_i N_i}{N_{tot}} = \sum_i \mu_i (B\%)_i \quad (3)$$

$$\bar{\beta} = \frac{\sum \beta_i N_i}{N_{tot}} = \sum_i \beta_i (B\%)_i \quad (4)$$

where μ and β represent the lognormal mean and standard deviation of the IM selected to represent the typological fragility curves defined in Sandoli et al. (2021) and summarized in Table 2, N_i is the number of building for the i -th class, while N_{tot} and $B\%$ are the total number and the percentage of each building class computed for each compartment, respectively (histograms in Fig. 8).

5 Urban compartment fragility curves at ULS

5.1 Fragility curves in terms of PGA

Urban compartment fragility curves for Rocca di Mezzo have been derived according to Eq. (1), considering the Minimum, Mean and the Maximum values of logarithmic mean μ indicated in Table 2. According to Eqs. (3) and (4), the weighted values of $\bar{\mu}$ and $\bar{\beta}$ have been calculated for each compartment, accounting for the percentage of the building classes. Table 3 summarizes the values of $\bar{\mu}$ and $\bar{\beta}$ derived by adopting the Mean values of μ listed in Table 2 for each building class, together with the building percentages corresponding to each class. As resulted from the CarTiS building inventory, only the classes URM-1 and URM-2 have been recognized in the twelve compartments of Rocca di Mezzo; then the values of $\bar{\mu}$ and $\bar{\beta}$ refer these two typologies only.

Figure 9 reports the PDF and CDF curves defined for the 12 urban compartments of Rocca di Mezzo, obtained by choosing the PGA as IM. In particular, in Fig. 9a are indicated the curves obtained by using Minimum values of the lognormal mean μ , in Fig. 9b those relative to the Mean values of μ and in Fig. 9c those relative the Maximum values of μ . Such curves, close to each other, highlight a not large range of variability of the fragility among the various compartments. This result was predictable due to the same building classes and the similar percentage of them included in each compartment. Nevertheless, the curves show that, for a given level of im , the compartments containing a greater percentage of buildings class URM-1 (compartment C03 or C04) have a higher exceeding probability than those including a greater number of building class URM-2 (compartment C05 or C12). This can represent a first important indicator to plan priority of interventions in such areas particularly vulnerable with respect to others.

With dashed black lines, the urban fragility curves calculated averaging among the 12 fragility curves are also reported in Fig. 9. These ‘mean-representative’ curves have been compared together in Fig. 10, aimed at representing the likelihood seismic damage scenario for whole town of Rocca di Mezzo (at ULS). In the same Fig. 10, the

Table 3 Logarithmic values of the distribution to derive the compartment fragility curves (obtained through the Mean values of μ)

Comp	Build classes	Build percentage (%)	μ	β	$\bar{\mu}$	$\bar{\beta}$
C01	URM-1	58	4.182	0.550	4.435	0.522
	URM-2	42	4.784	0.470		
C02	URM-1	45	4.182	0.550	4.513	0.511
	URM-2	55	4.784	0.470		
C03	URM-1	71	4.182	0.550	4.357	0.532
	URM-2	29	4.784	0.470		
C04	URM-1	77	4.182	0.550	4.321	0.537
	URM-2	23	4.784	0.470		
C05	URM-1	33	4.182	0.550	4.586	0.501
	URM-2	67	4.784	0.470		
C06	URM-1	64	4.182	0.550	4.399	0.526
	URM-2	36	4.784	0.470		
C07	URM-1	70	4.182	0.550	4.363	0.531
	URM-2	30	4.784	0.470		
C08	URM-1	63	4.182	0.550	4.405	0.526
	URM-2	37	4.784	0.470		
C10	URM-1	63	4.182	0.550	4.405	0.526
	URM-2	37	4.784	0.470		
C11	URM-1	69	4.182	0.550	4.369	0.530
	URM-2	31	4.784	0.470		
C12	URM-1	11	4.182	0.550	4.718	0.482
	URM-2	89	4.784	0.470		

exceeding probabilities corresponding to both the expected peak-ground accelerations provided IBC18 at ULS for Rocca di Mezzo ($a_g = 0.26 g$) and the acceleration estimated during the 2009 L'Aquila earthquake ($a_g = 0.06 g$) are also compared. As first remarking, the obtained urban fragility curves seem reliable and representative of the real damage scenario occurred following the 2009 L'Aquila's earthquake. In fact—based on what reported in the Reconstruction Plan of Rocca di Mezzo and on the inspections performed by the authors in situ—less than 40% of the buildings suffered medium/heavy damage level corresponding to ULS (i.e., DS4 according to EMS98) and very few of them collapsed. As second consideration, it is plausible that for an expected acceleration equal to $0.26 g$ (with a return period of 475 years) the 98% of the masonry buildings will suffer a high damaging, given the structural characteristics of the constructions.

The damage scenario predicted for a return period of 475 years reflects the actual ones observed in some epicentral areas struck by the most severe Italian earthquakes, for instance in Onna (2009 L'Aquila's earthquake) or in Sant'Angelo dei Lombardi (1980 Irpinia's earthquake) where the masonry building typologies, almost all medium/heavily damaged, were the same of those recognized in Rocca di Mezzo (Calderoni et al. 2011; D'Ayala and Panagoni 2011).

It should be noted that the proposed methodology is of general validity: (i) it can be developed by using other building classifications of existing masonry buildings available in literature (Rota et al. 2008; Lagomarsino and Cattari 2014), provided that the logarithmic values of mean (μ) and standard deviation (β) are known; (ii) it can be applied to other Italian historical centres, but it is required the knowledge of the masonry buildings characteristics (i.e., masonry arrangement, presence of seismic details, age of

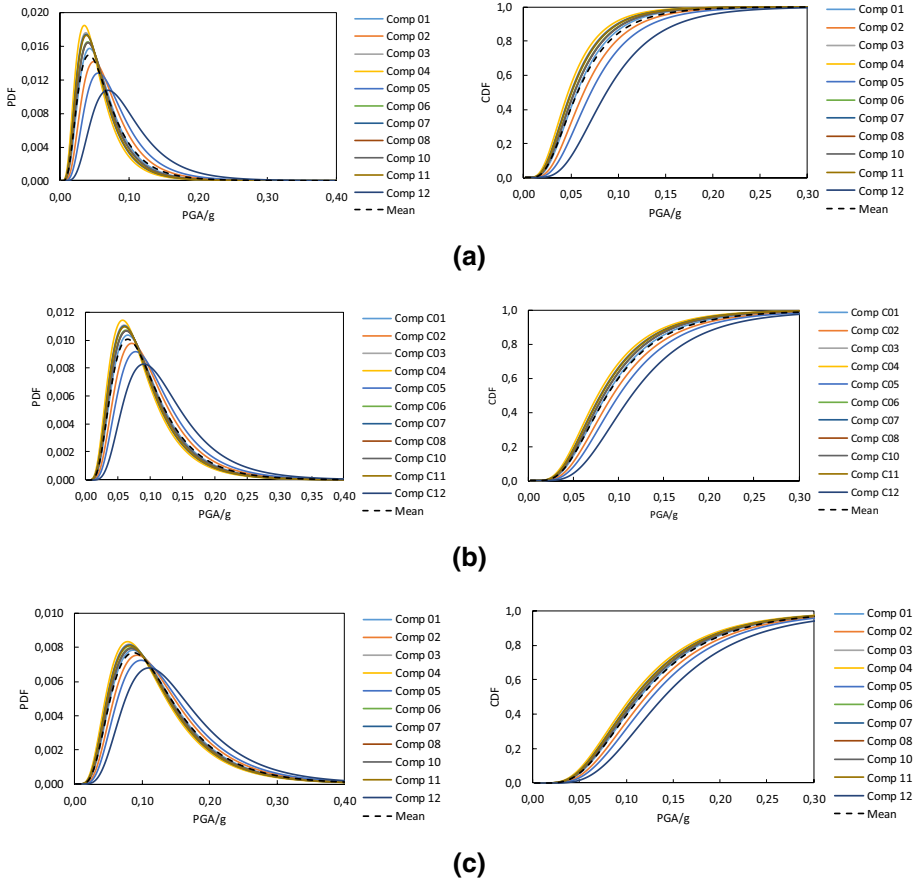
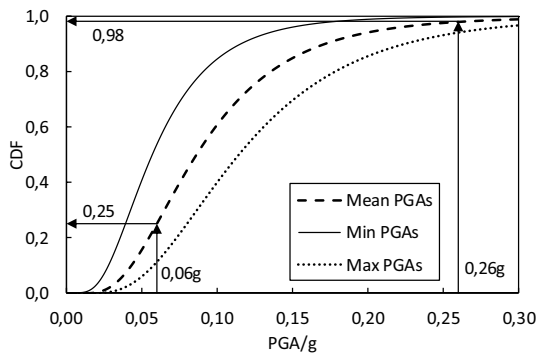


Fig. 9 Urban compartment fragility curves at ULS for Rocca di Mezzo obtained considering the Minimum, Mean and Maximum values of μ listed in Table X: **(a)** Minimum, **(b)** Mean, **(c)** Maximum

Fig. 10 Seismic vulnerability range defined by the urban fragility curves for Rocca di Mezzo and comparison with both expected (0.26 g) and occurred (0.06 g) peak-ground accelerations (following the 2009 L'Aquila earthquake)



construction, etc.) as for other methodologies available in literature (Formisano et al. 2010, 2017; Chieffo and Formisano 2019; Brando et al. 2021).

5.2 Fragility curves in terms of MCS intensity

Mercalli-Cancani-Sieberg (MCS) macro-seismic intensity scale comprises 12 intensity degrees, from ‘instrumental’ (degree 1) to ‘apocalyptic’ (degree 12). This intensity is widely employed in large-scale seismic vulnerability assessment because takes into account the severity of an earthquake as a function of both damage level suffered by buildings and people feeling due to shaking. Moreover, fragility curves in terms of MCS intensity are fundamental for comparing predicted damage scenario with the shake map in terms of MCS scale (Zuccaro et al. 2021).

To convert PGA in MCS intensity (I_{MCS}) still represents a topic under debate in the research field. Different correlation formulas between PGA and I_{MCS} are available in literature, all expressed with the following general form:

$$\log(PGA) = c_1 + c_2 I_{MCS} \tag{5}$$

where c_1 and c_2 are two coefficients derived by means of regression analyses referred to recordings of (Italian) earthquakes and to the related damage surveys. Suitable values of the coefficients c_1 and c_2 have been proposed in literature over the years (Margottini et al. 1992; Decanini et al 1995; Faccioli and Cauzzi 2006; Feanza and Michelini 2010; Cescatti et al. 2020). The values $c_1 = -1.33$ and $c_2 = 0.20$ suggested by Faccioli and Cauzzi (2006) have been adopted in the present paper, and motivated at the end of this Section.

The urban compartment fragility curves expressed in terms of I_{MCS} are represented in Fig. 11. Such curves, derived through the Eq. (1), give a continuous measure of the reaching or exceeding probability of the ULS for increasing intensity from grade 0 to grade 12. On the same graph, with black dashed lines is represented the average fragility curve (i.e., urban fragility curve) which can be considered mean-representative of the whole municipality of Rocca di Mezzo.

To validate the reliability of the fragility curves, the predicted damage scenario in terms of I_{MCS} has been compared with the real one observed in the aftermath of the 2009 L’Aquila’s earthquake. To this aim, the INVG shake map show that an I_{MCS} about 6.0 has

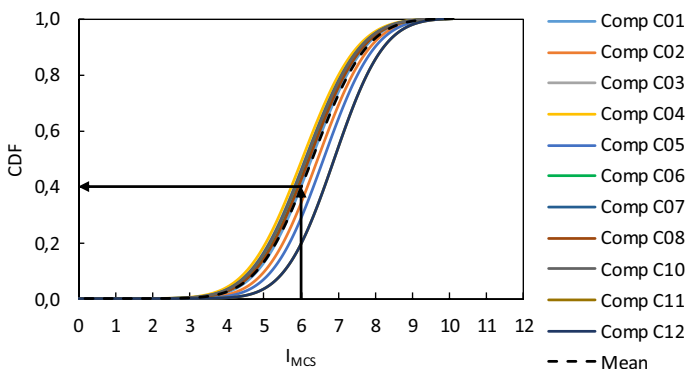


Fig. 11 Fragility curves in terms of MCS intensity scale for the urban compartment with indication of the average curve

been recorded in Rocca di Mezzo and its sub-municipalities (Fig. 4). By looking at Fig. 11, in correspondence of $I_{MCS}=6.0$ a 40% of exceeding probability at ULS is expected for the buildings included in the compartments, on average: it represents a plausible value of exceeding probability (even if slight higher with respect to the probability estimated in terms of PGA in the previous section) considering the damage scenario and the number of buildings affected by medium/heavily damage level after the 2009 earthquake.

As for the fragility curves expressed in terms of PGA, also in the case of MCS the urban compartments composed by a higher percentage of building classes URM-1 showed a greater exceeding probability than those comprising building classes URM-2 (for a given im_{MCS}).

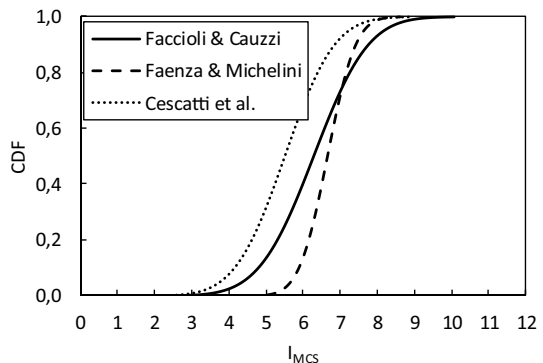
Going back to the effectiveness of the coefficient c_1 and c_2 used for correlating PGA with I_{MCS} (Eq. (5)), the average fragility curves of the whole municipality of Rocca di Mezzo—obtained by using the Faccioli and Cauzzi's proposal (2006)—have been compared with those obtained adopting other coefficients suggested by Feanza and Michelini (2010) and by Cescatti et al. (2020) in Fig. 12. It is resulted that for a given value of exceeding probability, the I_{MCS} intensities can differ among them in a range between one or two degrees. The fragility curve obtained by adopting the Faccioli and Cauzzi's coefficients averages the two curves calculated according to Feanza and Michelini (2010) and to Cescatti et al. (2020), at least for degree intensities from 3.0 up to 7.0–8.0. The same trend was observed in Gomez Capera et al. (2007) which compared I_{MCS} vs PGA using the coefficient c_1 and c_2 proposed by Feanza and Michelini (2010) and by Faccioli and Cauzzi (2006).

6 Multi-damage urban fragility curves

6.1 Definition of a damage scale

Urban compartment fragility curves presented in the previous Section allow for predicting damage scenarios relative to the achievement of the ULS (i.e., DS4 according to EMS98), for a given im . Nevertheless, it is recognized that fragility curves become a consistent tool if capable to envisage likelihood damage scenarios for multiple DSs. Multi-damage fragility curves are generally derived through pure empirical approaches, based on the statistical treatments of consistent data provided by post-earthquake damage surveys (Del Gaudio et al. 2019; Zucconi et al. 2021).

Fig. 12 Comparison between fragility curves obtained by adopting different correlation formulas between PGA and I_{MCS} proposed in literature (the fragility curves are the average ones for Rocca di Mezzo)



Often, to elaborate multi-damage fragility curves, either building classes and DSs were associated to those defined by the EMS98 (Rota et al. 2008): it identifies six classes of masonry buildings (indicated with the letters from A to F, with increasing vulnerability level) and five DSs (DS1 = negligible/slight damage, DS2 = moderate damage, DS3 = substantial/heavy damage, DS4 = very heavy damage, DS5 = collapse).

In Italy, the AeDES first-level post-seismic survey form for ordinary buildings has been used to derive multi-damage fragility curves. Basically, it allows for categorizing building characteristics and constructional details but—with respect to CarTiS form— the DS achieved by each structural and non-structural component are also estimated (Baggio et al. 2007). The damage scale adopted by AeDES is as follows: D0 = no damage, D1 = slight damage, D2–D3 = medium-severe damage, D4–D5 = heavy damage or collapse. Thus, with respect to EMS98, AeDES form includes the null damage level D0.

In literature, the DSs provided by AeDES relative to the principal components which governed the global seismic behavior of the constructions are employed to elaborate the multi-damage fragility curves. For instance, the component ‘vertical walls’ has been considered in Braga et al. (1982), Dolce and Goretti (2015) and Del Gaudio et al (2019). In some cases, the damage scale provided by AeDES has been correlated with that given by EMS98 and multi-damage fragility curves in terms of EMS98 obtained (Rota et al. 2008, Dolce and Goretti 2015).

Data coming from AeDES survey forms collected after the 2009 L’Aquila’s earthquake for the small centre of Rocca di Mezzo and its four sub-municipalities were available from the Reconstruction Plan. They have been processed for deriving multi-damage urban fragility curves, introducing a different correlation between the DSs provided by AeDES and EMS98.

The final scope of the AeDES survey form consists of providing a *usability* outcome relative to each detected building, as a result of different DSs assigned to each structural and non-structural component. In other terms, it is devoted to establish if, under the seismic sequence in progress the damaged buildings can be used by people protecting their human life reasonably (Baggio et al. 2007). Six usability outcomes are defined at the end of the form, indicated with the letter from A to F, whose meaning is summarized in Table 4. In the same Table, the conversion of the usability outcomes in the DSs provided by EMS98 herein proposed is reported.

With respect to other conversion approaches available in literature—i.e., based on the DS of the main structural component which governs the structural behavior—that presented in Table 4 appears more representative of the global seismic response of the buildings. It takes into account not only the DS of the predominant component (indirectly) but all those that participate in defining the global seismic response of the construction. It should be noted that a correspondence between the usability outcomes F and DS provided by EMS98 cannot be found, because it does not refer to a damage state of the building but to external risk.

6.2 Recognition of building class and damage states

AeDES usability outcomes relative to more than 1000 masonry buildings resulted by the Reconstruction Plan for the sub-municipality of Rocca di Mezzo. Consequently, the recognition of the building classes, and the urban fragility curves discussed in the following, refer to these four sub-municipalities.

Table 4 Correlation between usability outcomes provided by AeDES and DSs of EMS98

Usability outcome	Definition	EMS98
<i>A</i> (usable)	The building is usable, its safe was not compromised by the occurred earthquake	DS0*
<i>B</i> (temporary unusable)	The building is completely or in part unusable, but it can be used following to first aid interventions	DS1
<i>C</i> (partially unusable)	Only a single part of the building is unusable	DS2
<i>D</i> (temporary unusable/needs to be reviewed)	The damage state makes the building temporary unusable, waiting for more detailed survey	DS3
<i>E</i> (unusable)	Due to damaging, the building cannot be used (not even following first aid interventions)	DS4
<i>F</i> (unusable)	The building is unusable due to external risk induced by adjacent contractions	(none)

*DS0 was introduced by the author, it is not contained in the EMS98

Table 5 Percentage and number of buildings detected for each sub-municipality

Sub-municipalities	Compart-ments	# URM-1	# URM-2	Tot. num build	% URM-1 (average)	% URM-2 (average)
Rocca di Mezzo	C01	384	287	671	57	43
	C02					
	C03					
Terranera	C04	144	57	201	72	28
	C05					
Rovere	C06	169	93	262	65	35
	C07					
	C08					
	C09					
Fonteavignone	C10	54	38	92	59	41
	C11					
	C12					

Table 5 summarizes number and percentage of URM buildings detected through the AeDES forms, considering the two building classes URM-1 and URM-2 identified for the case study through CarTiS database. The table reports also the number of the urban compartments defined by CarTiS for each sub-municipality: such correspondence has been used to calculate the real percentages of building classes enclosed in each sub-municipality.

Histograms indicated in Fig. 13 report the total number and the percentage of the buildings detected in each sub-municipality, correlated with the usability outcomes/damage scale of EMS98 defined in Table 4. While, Fig. 14 represents the same data but relative to entire Municipality of Rocca di Mezzo. Regarding the whole municipality (Fig. 14), the great part of the masonry buildings (about 65%) resulted without damage (i.e., usability outcome A/damage level DS0); while, more than 20% of them achieved a severe damaging

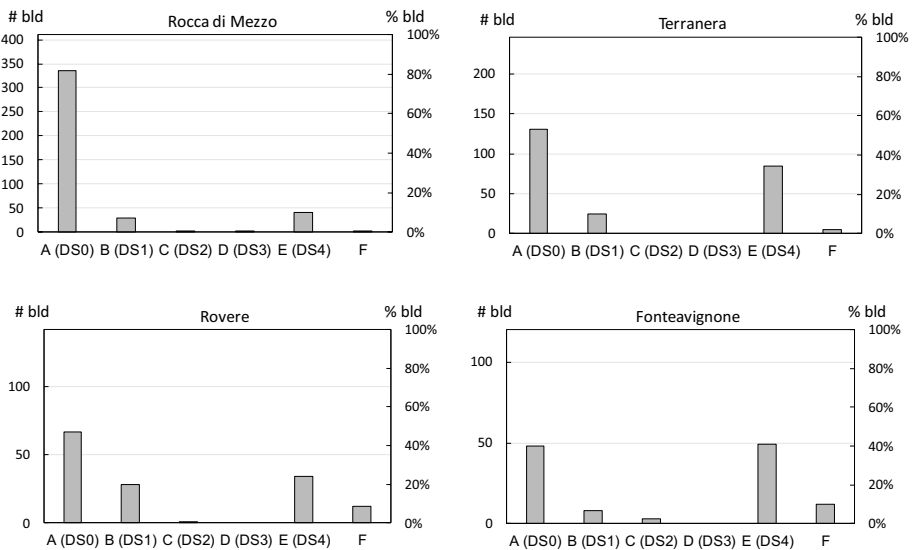
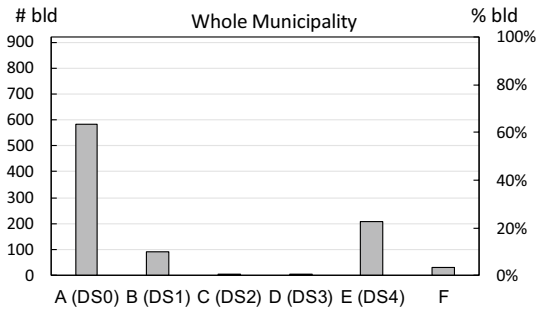


Fig. 13 Usability outcomes from damage surveys after the 2009 L'Aquila earthquake for the sub-municipalities of Rocca di Mezzo

Fig. 14 Usability outcomes from damage surveys after the 2009 L’Aquila’s earthquake for the whole municipality Rocca di Mezzo



associated to a usability outcome E (i.e., damage level DS4). Referring to the single sub-municipalities, Fonteavignone and Terranera are those with a greater percentage of buildings involved by severe damages (DS4), while few buildings collapsed.

In general, few buildings have been classified with usability outcomes B, C or D. This appears consistent with the AeDES purpose: the post-earthquake inspections are rapid surveys aiming to ensure the human life safeguard. Consequently, the two outcomes A and E tends to prevail than others: the outcome A ensure that the building is safe and then the human life is not compromised, while the outcome E states that the building is sufficiently damaged and cannot be used by people. It is interesting to point out that the percentages of the AeDES outcomes recorded for Rocca di Mezzo agree with the results obtained on the whole Abruzzi region after the 2009 L’Aquila earthquakes, as discussed in Dolce and Goretti (2015).

6.3 Derivation of multi-damage fragility curves

Multi-damage urban fragility curves have been derived through the methodology presented in Sect. 4, adopting the lognormal distribution given by Eq. (1) ruled by logarithmic mean ($\bar{\mu}$) and standard deviation ($\bar{\beta}$).

In order to calculate $\bar{\mu}$ and $\bar{\beta}$ for each sub-municipality, the logarithmic mean (μ) and standard deviation (β) referred to the different DSs of the basic typological classes (URM-1 and URM-2) are needed. Suitable values of μ and β for the Italian masonry building classes referred to the five DSs of the EMS98 are suggested in some literature works (Rota et al. 2008; Cattari and Lagomarsino 2014; Del Gaudio et al. 2019; Donà et al. 2020). In this paper, the semi-empirical values μ and β proposed in Lagomarsino and Cattari (2014) have been used and summarized in Table 6. Instead, the correspondence between building classes of EMS98 with those adopted in this paper (Table 1) has been already discussed in

Table 6 Values of logarithmic mean μ and standard deviation β provided by Lagomarsino and Cattari (2014) for DS defined by EMS98

Damage State	URM-1		URM-2	
	μ	β	μ	β
DS0	0.000	0.51	0.000	0.57
DS1	0.042	0.51	0.069	0.51
DS2	0.075	0.53	0.123	0.53
DS3	0.120	0.53	0.199	0.53
DS4	0.194	0.53	0.321	0.54

Sandoli et al. (2021): building classes A and B of the EMS98 correspond to URM-1 and URM-2, respectively.

The values of μ and β listed in Table 6 have been transformed in weighted average values $\bar{\mu}$ and $\bar{\beta}$ through the Eqs. (3) and (4), such that they are representative of the whole set of masonry buildings included in each sub-municipality (Table 7).

Multi-damage fragility curves obtained for the sub-municipalities of Rocca di Mezzo—for increasing damage level from DS0 to DS4—are showed in Fig. 15, in terms of both PGA and I_{MCS} . Coherently with the curves presented in Sect. 5, PGA and I_{MCS} have been correlated with the formula proposed by Faccioli and Cauzzi (2006).

Figure 15 shows that the curves relative to DS4 are shifted towards with respect to those corresponding to DS0, while the intermediate ones are close one to other. This appears reasonable considering (i) the similar (and reduced) percentage of building affected by damage level DS1, DS2 and DS3 and that (ii) the values of μ and β increase slightly passing from one to other damage state.

As a comparison, the fragility curve relative to the DS4 obtained through the (semi-empirical) values μ and β proposed in Lagomarsino and Cattari (2014) (Table 6) have been compared with those obtained by using the μ and β provided in Table 2 (Sandoli et al. 2021) in Fig. 16. In particular, three fragility curves for each sub-municipality have been represented, each corresponding to the Minimum, Mean and Maximum value of μ proposed in Table 2. As a consequence, a range of the likelihood damage scenarios has been identified (indicated with solid grey). In such figure with the symbols ‘Min (DS4)’, ‘Mean (DS4)’ and ‘Max (DS4)’ are indicated the curves calculated by adopting the Minimum, the Mean and the Maximum value of μ defined in Table 2, respectively. The urban scale fragility curves proposed by Lagomarsino and Cattari (2014) resulted moved toward with respect to the grey range, but a good accordance with respect to the curves referred to the Maximum value of μ resulted. Such differences are not surprising, and justified by the different approaches used to derive μ and β : in Sandoli et al. (2021) they have been derived through a mechanical approach, which is known to provide conservative values with respect to the empirical-based one adopted in Lagomarsino and Cattari (2014). On the other side, data derived via numerical analyses are affected by uncertainties on structural modelling and on material properties and by safety coefficients of materials (i.e., knowledge level) given by the codes to perform seismic analyses. Instead, empirical data are obtained post-processing post-earthquake survey information and (i) tends to overestimate the observed damage because aimed at expressing usability outcomes, (ii) the judgement

Table 7 Values of the lognormal mean and standard deviation relative to each sub-municipality

DS	Sub- municipality	$\bar{\mu}$	$\bar{\beta}$	Sub- municipality	$\bar{\mu}$	$\bar{\beta}$
DS0	Rocca di	0.000	0.537	Terranera	0.000	0.528
DS1	Mezzo	0.054	0.511		0.050	0.511
DS2		0.095	0.533		0.088	0.533
DS3		0.154	0.528		0.142	0.528
DS4		0.249	0.537		0.203	0.534
DS0	Rovere	0.000	0.5.32	Fonteavignone	0.000	0.536
DS1		0.052	0.511		0.053	0.511
DS2		0.092	0.533		0.094	0.533
DS3		0.148	0.528		0.153	0.528
DS4		0.216	0.497		0.246	0.343

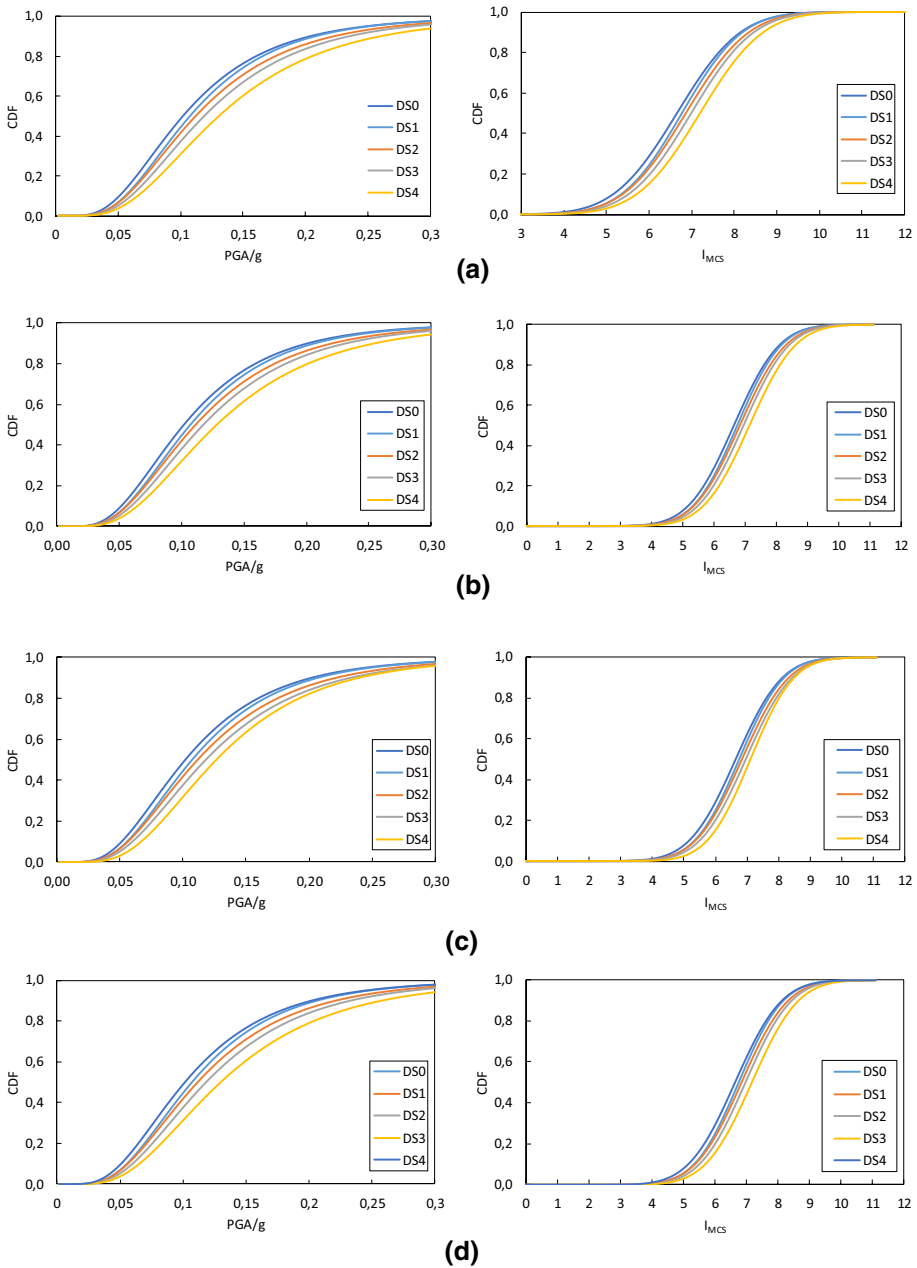


Fig. 15 Multi-damage urban fragility curves in terms of PGA and I_{MCS} : (a) Rocca di Mezzo, (b) Terranera, (c) Rovere, (d) Fonteavignone

on the damage level is affected by the expertise of the detector. Anyway, in the framework of these approximations, the comparisons between the curves is acceptable for seismic vulnerability assessment at urban-scale.

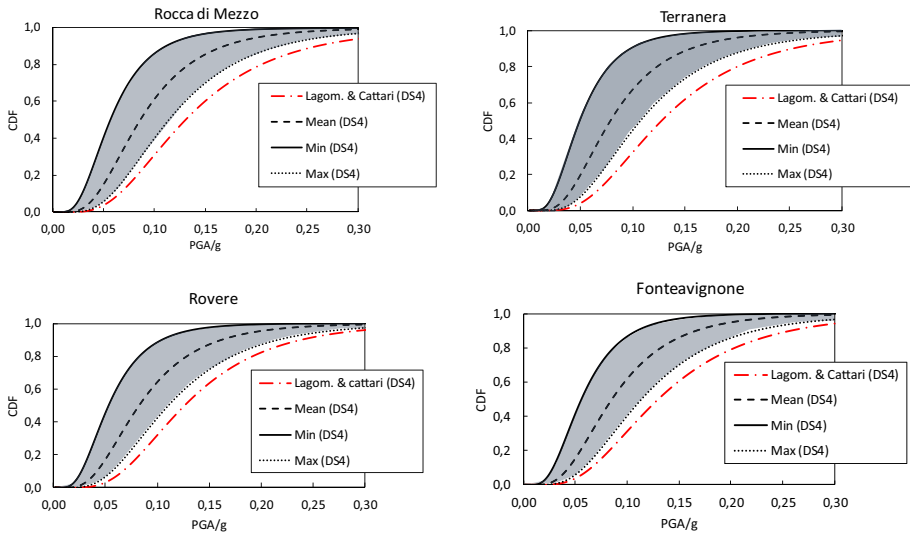


Fig. 16 Comparison of the urban fragility curves provided by the authors with those of Lagomarsino and Cattari (2014) for the damage level DS4

6.4 Damage probability matrices

Damage Probability Matrix (DPM) represents the probability that a building will experience a particular level of damage as a result of a particular intensity (Whitman et al. 1973). Such probability is obtained by cumulating the frequencies (mass density function) from the highest to the lowest level of damage (Rota et al. 2008). In other terms, they provide a distribution of damage in different levels for a preselected ground motion intensity (Rosti et al. 2020a, b).

DPMs are generally used to derive multi-damage fragility curves in empirical-based methods, where data collected through DPMs are fitted to obtain continuous probability density functions (Braga et al. 1982). DPMs can also be obtained by means of mechanical approaches, using statistical simulations of building-types (e.g., Monte Carlo analyses) and performing nonlinear incremental dynamic analyses (Singhal and Kiremidjian 1996), or by means of expert-judgement approach (ATC1985). Instead, Kappos et al. (2006) derived DPMs based on a hybrid procedure combining empirical with the mechanical approach.

Commonly, the binomial distribution best fits the damage distribution and then it is frequently used for seismic large-scale vulnerability assessment, but also the lognormal distribution is suggested by ATC1985 (Calvi et al. 2006). A consistent discussion on the feasibility of the different statistical distributions can be found in Calvi et al. (2006) or in Rosti et al. (2020a, b).

In the present research, a hybrid-based procedure has been chosen to derive urban DPMs: data collected from the post-earthquake AeDES usability outcomes (which provided the percentage of the DSs achieved in each sub-municipality) have been combined with results of numerical analyses (which provided mean and standard deviation of the distribution). The urban DPMs have been derived a-posteriori for estimating a measure of the cumulative probability of occurrence of each DS, for a given seismic intensity measure im of IM, in the considered urban area.

The DPMs for Rocca di Mezzo, Terranera, Rovere and Fonteavignone have been constructed by using the discrete values of damage probability provided by the lognormal distribution of the PDF, for a give *im*. The results have been represented by means of the histograms reported in Fig. 17 and give a measure of a likelihood damage distribution for increasing I_{MCS} , from 4.0 to 12. As expected, the damage distribution becomes more severe for increasing I_{MCS} : passing from $I_{MCS} = 4.0$ to $I_{MCS} = 12$ the probability of achieving a potential damage DS4 increases while the probability to reach DS0 decreases.

The results obtained through the DPMs are encouraging: in correspondence of the *im* recorded during the 2009 L'Aquila earthquake—i.e. $I_{MCS} = 6.0$ —the probability of achieving a damage level DS4 is about 20–30%, this agree with the building percentage classifies with E resulted from AeDES surveys. Instead, the comparisons between DPMs and in-situ surveys provided by AeDES for the damage level from DS1 to DS3 resulted less comparable: this probably depends on the similar and the reduced percentages of buildings classified between B to D during the post-earthquake inspections.

7 Conclusions

A novel hybrid methodology devoted to predict likelihood seismic damage scenarios for medium and small Italian historical centers, through urban fragility curves and damage probability matrices, has been presented in this paper. The method combines the expert-judgement approach with the mechanical one: the first provides the buildings classes to recognize in the urban areas, while the second give the statistical parameters to develop the fragility functions.

Usually, typological fragility curves are adopted for large-scale seismic assessment (e.g., referred to a single building class). In this study, the concept of fragility has been expanded by introducing the idea of the *urban* fragility curve, intended as a single curve

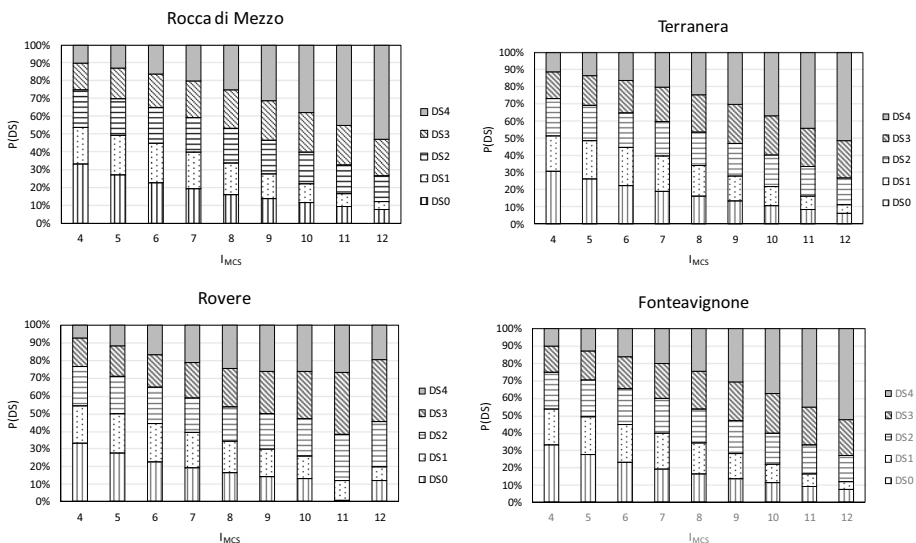


Fig. 17 Damage probability matrices for the sub-municipalities of Rocca di Mezzo

‘mean-representative’ of the seismic fragility of an entire area depending on building classes and their percentage enclosed.

In the first part of the research, urban fragility curves have been developed with application to the case study of Rocca di Mezzo (a small urban centre in the district of L’Aquila, Italy). Building inventory has been derived by exploration of the CarTiS database, from which more than 1000 masonry buildings are resulted. Such buildings have been categorized within the five masonry building classes proposed in Sandoli et al. (2021), resulting the two types URM-1 and URM-2 only. By applying the proposed methodology, urban fragility curves in terms of both PGA and MCS intensity have been elaborated for the twelve urban compartment defined by CarTiS for Rocca di Mezzo, representative for a damage level damage DS4 according to EMS98.

In addition, multi-damage urban fragility curves and DPMs have been also developed, according with the DSs given by EMS98. To this aim, (i) a new damage scale based proposed, defined by converting of the usability outcomes provided by AeDES in the DSs provided by EMS98, (ii) damage surveys data provided by AeDES, in combination with the building classes identified through the CarTiS database, have been processed to define likelihood seismic damage scenarios.

To assess the feasibility of the methodology, data coming from damage scenarios after the 2009 L’Aquila’s earthquake—in terms of both maximum PGA and MCS intensity recorded for Rocca Mezzo—have been used as a comparison. Results showed that the predicted damage scenarios are representative of the actual ones: after the earthquake, less than 40% of the buildings suffered medium/heavy damage level corresponding to DS4 and very few of them collapsed due to the shaking recorded in Rocca di Mezzo, as predicted throughout the methodology too. In addition, also for high-intensity earthquakes (i.e., $a_g = 0.26 g$ provided by the Italian code for Rocca di Mezzo at ULS) the damage prediction appeared plausible, if compared with actual damage scenarios occurred in other Italian historical centres composed by similar building classes and hit by medium or severe seismic accelerations.

The achieved results showed that the methodology can be a useful tool for planning mitigation strategies devoted to define priority of intervention in areas more vulnerable than others or to support post-earthquake emergency phases through real time-time loss estimations, with acceptable level of approximation and in rapid time intervals. In the future the authors will focus on developing a web-GIS application, accounting for hazard and exposure level, with the purpose of evaluating the global seismic risk of an entire urban area.

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Declarations

Competing interests The authors have not disclosed any competing interests.

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