CrossMark

ORIGINAL RESEARCH PAPER

# Empirical fragility curves from damage data on RC buildings after the 2009 L'Aquila earthquake

Carlo Del Gaudio[1] · Giuseppina De Martino[1] ·
Marco Di Ludovico[1] · Gaetano Manfredi[1] · Andrea Prota[1] ·
Paolo Ricci[1] ⓘ · Gerardo Mario Verderame[1]

**Abstract** The study analyses the data related to a database of 7597 private Reinforced Concrete buildings located in the city and the province of L'Aquila surveyed after the 2009 earthquake. Survey data were collected by the Italian Department of Civil Protection during post-earthquake usability inspections including information on building characteristics, level and extent of damage to structural and non-structural components. For each building, the Peak Ground Acceleration demand has been determined according to data available from the ShakeMap of the event and the georeferenced building location. The analysis of data highlights the key role played by the damage to non-structural components—namely, infills and partitions. Damage Grades according to the European Macroseismic Scale EMS-98 have been derived from damage data to single building components. Two building classes have been defined in the study in order to investigate the influence of number of storeys of buildings on the observed damage. Damage Probability Matrices have been derived for the assumed building classes and bins of Peak Ground Acceleration, and

✉ Paolo Ricci
  paolo.ricci@unina.it

  Carlo Del Gaudio
  carlo.delgaudio@unina.it

  Giuseppina De Martino
  giuseppina.demartino2@unina.it

  Marco Di Ludovico
  diludovi@unina.it

  Gaetano Manfredi
  gamanfre@unina.it

  Andrea Prota
  aprota@unina.it

  Gerardo Mario Verderame
  verderam@unina.it

[1]  Department of Structures for Engineering and Architecture, University of Naples Federico II, Via
    Claudio, 21, Naples, Italy

 Springer

observed trends are analyzed. Different methodologies for estimating fragility functions from data on Damage Grades and Peak Ground Acceleration demand are illustrated, discussed and applied to the database, leading to the derivation of EMS-98-based fragility curves for the defined building classes. Finally, the proposed fragility curves are compared with main empirical fragility curves for RC buildings from literature studies.

## 1 Introduction

Italian earthquakes of the last three decades have highlighted the high seismic vulnerability of the existing building stock, as demonstrated by the significant human, financial and functionality losses due to the severe damage suffered by structural and non-structural components observed after moderate-to-high magnitude events. Therefore, there is a growing interest in seismic fragility assessment of buildings at regional and urban scale.

In this study, starting from observational damage data collected after the 2009 L'Aquila earthquake, the structural and non-structural damage to the Reinforced Concrete (RC) buildings is analysed, and empirical fragility curves are derived.

Generally speaking, a seismic fragility assessment can be carried out by means of analytical or empirical methods.

Analytical methods are based on the use of numerical models providing the expected damage (typically corresponding to a fixed displacement threshold) as a function of the seismic intensity. Several approaches have been developed in literature, different from each other both in structural (usually simplified) modelling and in seismic capacity assessment procedure. Among them, methods based on simplified mechanics-based procedures (e.g. Cosenza et al. 2005; Borzi et al. 2008), Capacity Spectrum Methods (e.g. Iervolino et al. 2007; Del Gaudio et al. 2015), and Displacement-Based methods (e.g. Calvi 1999; Crowley et al. 2004; Borzi et al. 2008).

In empirical methods the assessment of the expected damage to a building is based on the observation of damage suffered during past seismic events. Empirical methods have the advantage of providing a realistic damage estimation since they are derived from observed post-earthquake damage data. Hence, their reliability is related to the quality and amount of data they are based on. For instance, depending on the available building dataset, it may be necessary to convert and homogenize damage data collected in different surveys into a unique damage scale.

As far as Italian earthquakes are concerned, one of the first seismic vulnerability assessment methods based on observational data was developed in (Braga et al. 1982), based on the data collected after the 1980 Irpinia earthquake. The database consisted of 36,000 buildings, with about 3000 RC buildings. The study derived Damage Probability Matrices (DPMs, which express in a discrete form the conditional probability of reaching a given damage grade due to a given seismic intensity) based on macroseismic intensity and vulnerability classes defined according to Medvedev–Sponheuer–Karnik (MSK-76) scale (Medvedev 1977). The authors identified the damage to the building with the damage to the vertical structures. The attribution of the different structural types (i.e. RC and masonry buildings, and, in the latter case, distinguishing between the type of vertical and horizontal

structure.) to the MSK vulnerability classes (from A to C), the assignment of macroseismic intensities to the Municipalities and the derivation of the DPMs were obtained through a Likelihood maximization process.

Sabetta et al. (1998) derived fragility curves from data on 50,000 buildings collected after Italian earthquakes as a function of a mean damage index, specifically derived for each Municipality, according to the MSK scale and different strong motion parameters provided by attenuation relationships. Orsini (1999) derived fragility curves from the surveys carried out after the 1980 Irpinia earthquake through the use of the Parameterless Scale of Intensity (PSI) (Spence et al. 1991).

A reference work was developed by Lagomarsino and Giovinazzi (2006), which proposed two approaches, a "macroseismic" and a "mechanical" method. Following the macroseismic approach, fragility curves are derived for different building types and subtypes from the DPMs implicitly defined by the European Macroseismic Scale EMS-98 (Grünthal 1998).

Rota et al. (2008) analyzed damage data on 150,000 buildings from past Italian earthquakes, from Irpinia (1980) to Molise (2002), in order to derive fragility curves through advanced nonlinear regression methods for several building types. The authors defined different building classes, depending on vertical structure (masonry, RC, mixed or steel), number of storeys, layout regularity and horizontal structure in the case of masonry buildings, and type of design (seismic or non-seismic) in the case of RC buildings. The database included about 12,000 RC buildings. Only data from Irpinia (1980) earthquake contributed to the range of Peak Ground Acceleration (PGA) >0.3. The observed damage was defined based on vertical structures only, not accounting for non-structural infill components. Moreover, due to the reduced amount of data (about 600 buildings), fragility curves were not provided for RC buildings with seismic design and number of storeys greater or equal than 4 (Medium/High-rise).

Zuccaro and Cacace (2009) proposed DPMs based on EMS-98 damage scale from empirical damage data on 170,000 buildings, collected after different Italian earthquakes, from Irpinia (1980) to Etna (2002), for the EMS-98 vulnerability classes. The database was mainly made up of masonry buildings belonging to EMS-98 vulnerability classes A to D, and the remaining part included RC buildings belonging to EMS-98 vulnerability classes C and D. Unfortunately, no clear indication is reported by the authors regarding the number of RC and masonry buildings in each vulnerability class, and it is not possible to deduce the number of RC buildings with seismic design included in the database (Zuccaro 2004). In (Zuccaro and Cacace 2015) the authors proposed a methodology aimed at reducing the uncertainty in the vulnerability classification of EMS-98 through "vulnerability factors", including, among others, the number of storeys and the construction age.

In the following, a geo-referenced database of 7597 residential RC buildings surveyed after the 2009 L'Aquila earthquake—which represents a subset of the about 70,000 buildings inspected under the coordination of DPC (Dolce and Goretti 2015)—is analyzed. Team of surveyors carried out field inspections on these buildings in the immediate post-earthquake; the AeDES survey form (Baggio et al. 2007) was adopted as a tool for the seismic damage and usability assessment. Although the aim of the AeDES form is to evaluate building usability in the post-earthquake emergency, it includes data on building characteristics (e.g. number of storeys, construction age) and on level and extent of damage to different building components (e.g. vertical structures, horizontal structures, stairs, floors, roof, infills/partitions).

Such data are analysed, evaluating the distribution of damage depending on building characteristics and PGA demand (the latter is provided by the ShakeMap of the event, based on the location of the buildings). A very significant role of the non-structural damage affecting infill components is highlighted, as already described by previous studies (Ricci et al. 2011; Verderame et al. 2011, 2014; Liel and Lynch 2012; De Luca et al. 2015; Di Ludovico et al. 2016a).

Then, the data on level and extent of structural and non-structural damage collected by the AeDES forms are elaborated in order to derive, for each building, a damage grade defined according to EMS-98 (Grünthal 1998). Building classes are defined, depending on the number of storeys.

Based on the elaborated damage data, DPMs for spatially extended grids are derived; finally, different methodologies for seismic fragility estimation are illustrated, and fragility curves for the defined building classes are derived and discussed.

## 2 Seismic input characterisation

On April 6th, 2009, an earthquake of magnitude $M_w = 6.3$ struck the Abruzzo region, killing 308 people. The area near the epicenter, in the neighborhood of L'Aquila Municipality, was seriously damaged, resulting in a IX–X grade of MCS (Mercalli–Cancani–Sieberg) macroseismic scale.

Soon after the earthquake, the Italian National Institute of Geophysics and Volcanology (*Istituto Nazionale di Geofisica e Vulcanologia*, INGV) published a ShakeMap of the event (http://shakemap.rm.ingv.it/shake/index.html). This was generated through the software package ShakeMap® developed by the U. S. Geological Survey Earthquake Hazards Program (Wald et al. 2006) specifically designed to obtain maps of the peak ground motion parameters (Michelini et al. 2008).

The data used to obtain the real-time maps are provided mainly by the INGV broadband stations, some of which paired with strong motion sensors, in addition to strong motion data obtained from the Italian Strong Motion Network (*Rete Accelerometrica Nazionale*, RAN). The peak ground motion parameters (e.g., PGA and spectral pseudo-acceleration for different periods of vibration) are determined through different Ground Motion Prediction Equations (GMPEs):

- for events with $M_w \leq 5.5$: three separate sets of equations GMPEs for six main regions are used, specifically determined using the largest number of available data for the area of interest.
- for events with $M_w > 5.5$ (as in our case): the relations of Ambraseys et al. (1996) and Bommer et al. (2000) are used for PGA and PGV, respectively.

The procedure implemented by the INGV accounts for site effects through a nationwide 1:100,000 geological map calibrated against the average shear wave velocity of the top 30 m of the subsurface profile ($V_{S30}$).

Figure 1 reports the ShakeMap of the April 6th, 2009 event, with PGA values from 0 to 0.50 g along with the location of each geo-referenced RC building analyzed in this work. Hence, for each building the corresponding PGA value can be extrapolated from the shake map provided by INGV.
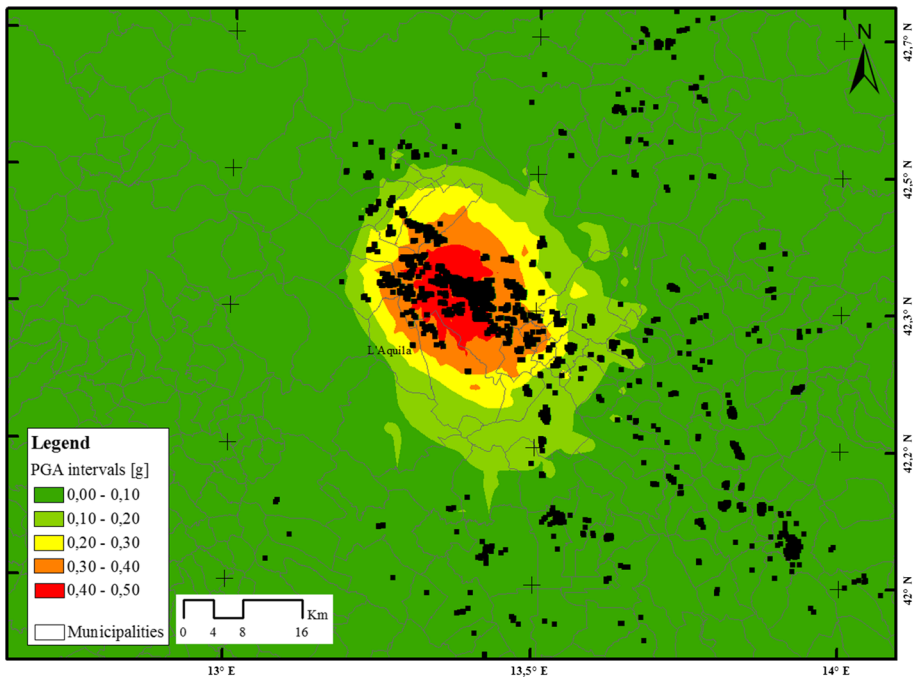
**Fig. 1** Shake map data (http://shakemap.rm.ingv.it/shake/index.html) and spatial distribution of 12,223 RC buildings dataset (*black squares*)

## 3 Empirical data after L'Aquila earthquake

The empirical data collected during L'Aquila post-earthquake surveys are presented in this section. The 2009 L'Aquila (Abruzzi Region) earthquake hit 130 municipalities (Dolce and Goretti 2015) and caused extensive damage to public and private structures, to artistic and cultural heritage of L'Aquila and provinces. Few days after the earthquake, the damage and usability assessment of the buildings started to determine whether they could be safely used in the case of aftershocks.

The damage and usability assessment of ordinary buildings, defined as structural units of ordinary construction types (typically masonry, reinforced concrete or steel, etc.), was performed by means of the first level survey form, the AeDES form (Baggio et al. 2007).

The form was developed between 1996 and 1997 by a joint working group National Seismological Service (SSN)—Group National Defense against Earthquakes (GNDT). In a preliminary version, this form was firstly used to assess the usability of buildings damaged by the 1997 Umbria–Marche earthquake. The form was updated after destructive earthquakes, such as 1998 Pollino, 2002 Molise and 2009 L'Aquila earthquakes. The field inspections carried out after L'Aquila earthquake allowed to collect a database containing first-level data (e.g. structural type, construction age, number of storeys, average storey surface, damage to structural and non-structural components, and building usability rating), on 74,254 buildings (Dolce and Goretti 2015).

Out of 74,254 buildings, 80 % of the dataset concerns RC or masonry buildings (12,223 RC buildings and 47,077 masonry buildings, respectively), 9 % buildings with a mixed structural type (i.e. comprising RC and masonry structural members) steel structure or

other types. For the remaining 11 % of the dataset, the structural type of buildings was not available from the AeDES form.

The analysis of damage suffered by the different structural type is reported in (Dolce and Goretti 2015). Masonry buildings were classified in three vulnerability classes (poor, medium and good quality) depending on the characteristics of the vertical (layout regularity, quality and presence of ties/tie beams) and the horizontal (i.e. vaults w/or w/o ties, floor rigidity) structures. The response of RC buildings was analysed depending on the number of storeys and the construction age. The authors point out a clear distinction between the behaviour of different building classes. The mean non-dimensional damage, defined as the weighted average of the damage grades to the vertical structures only, decreased going from poor-, medium-, good-quality masonry, RC and steel buildings. Mixed type buildings show a behaviour between medium- and good-quality masonry buildings. Furthermore, the authors compare the damage due to the L'Aquila earthquake with the damage due to some recent Italian earthquakes, such as the 1980 Irpinia and the 2002 Molise earthquakes. They note that good-quality masonry buildings and RC buildings behaved much better in the 2009 L'Aquila earthquake than in the 1980 Irpinia earthquake, due to the enforcement of the seismic design in the L'Aquila territory since 1915 (R.D.L. n. 573, 1915). On the contrary, this trend was not confirmed for poor- or medium-quality masonry buildings, since they are typically dated back to before 1919 and hence without any seismic code provision.

The damage shown by RC buildings, which is the focus of the present study, is herein illustrated in detail starting from the analysis of the database and of the damage reported by the AeDES survey forms.

First, a subset of 9152 RC buildings was investigated (i.e. about 75 % of the 12,223 RC buildings inspected), characterized by a residential use and located in Municipalities classified with macroseismic intensity in the Mercalli-Cancani-Sieberg (MCS) scale (Sieberg 1930) ($I_{MCS}$) higher than VI. This because only in these Municipalities a building by building survey was carried out, whereas in the remaining Municipalities the survey was carried out only under request by the owner (Dolce and Goretti 2015). Only data from completely surveyed Municipalities are used because, in such a way, the percentages of damaged buildings can be estimated based on complete samples, thus avoiding possible biases due to the presence of non-surveyed (likely because undamaged) buildings within the investigated Municipalities.

Among the subset, 8750 are Moment Resisting Frame (MRF) RC Buildings. The remaining 402 are RC buildings with shear walls, which are discarded from the present case study, due to their different response under seismic action.

In Fig. 2 the isoseismic units—i.e. PGA bins—assumed in this work are reported. The lower limit is 0.025 g, which is equal to the lower PGA value estimated from the ShakeMap for the considered buildings. Therefore, five isoseismic units are considered, ranging from 0.025 to 0.50 g, with a step of 0.10 g.

Figure 2 shows that Municipalities with $I_{MCS} >$ VI (hatched in grey) do not cover uniformly the assumed PGA bins. As clearly expected, the lower the PGA demand, the lower the macroseismic intensity, and the lower the occurrence of $I_{MCS} >$ VI. In particular, within the lowest PGA bin (0.025–0.10 g) the building dataset represents only a minor part of the building stock, i.e. 5.1 %, according to census data (ISTAT 2011). In these cases, a "threshold of completeness" within the isoseismic units is usually assumed in order to establish if consider or not the data. This threshold varies, in literature, from 60 to 80 % (Goretti and Di Pasquale 2004; Sabetta et al. 1998; Rota et al. 2008), in all cases much
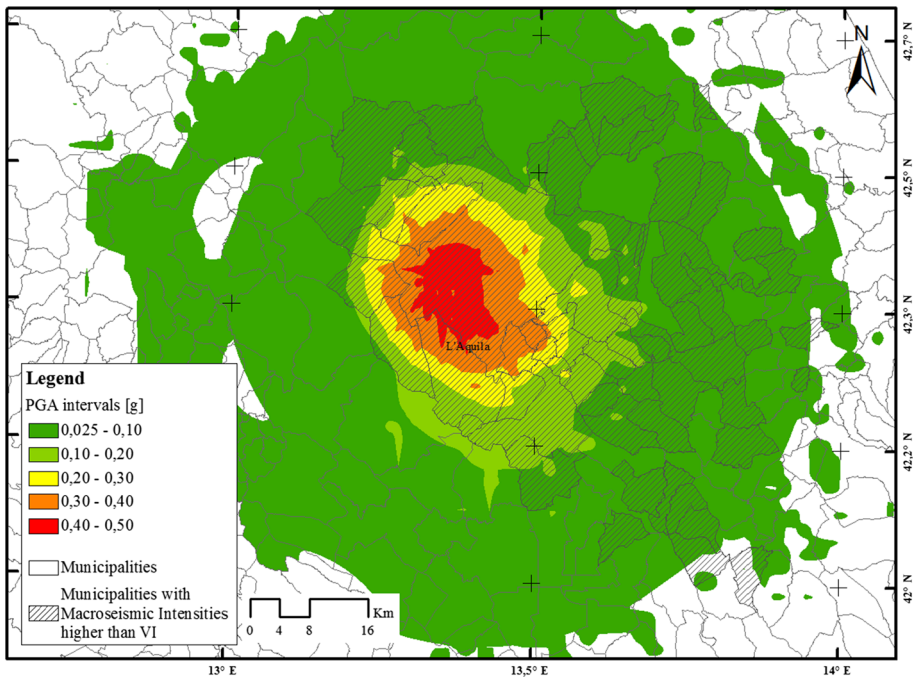
**Fig. 2** Isoseismic areas corresponding to the assumed PGA bins form 0.025 to 0.50 g and Municipalities classified with MCS intensity higher than VI

higher than 5.1 %. Thus, buildings in Municipalities with $I_{MCS} > VI$ located in PGA bin (0.025–0.10 g) have been removed from the dataset.

As a further evidence to such assumption, note that considering data from Municipalities with $I_{MCS} > VI$ in the 0.025–0.10 g PGA bin could lead to a bias because it is likely to assume that these Municipalities are the ones characterized by the most vulnerable buildings within the isoseismic unit.

According to such assumptions, the final subset consists of 7597 MRF residential RC buildings.

Figure 3 reports the frequency and the cumulative percentage of the buildings as a function of the construction age, number of storeys and average storey surface. The construction age is classified according to eight periods (i.e. before 1919, between 1919 and 1945, 1946–1961, 1962–1971, 1972–1981, 1982–1991, 1991–2001, after 2001) as commonly adopted in the census data collections (and in the AeDES form). Figure 3a shows that 87 % of the building dataset (corresponding to 6616 buildings) was built after 1972; the graphs in Fig. 3b, c) show that 85 % of the building dataset (corresponding to 6482 buildings) had a number of storeys between 2 and 4, while 67 % of the building dataset (corresponding to 5131 buildings) had an average storey surface between 70 and 230 m². Section 4—Damage to the structural components—of AeDES form gives information on level and extent of damage detected on structural components: vertical structures, floors, stairs, roofs and infills–partitions. Note that infills–partitions are included by AeDES form in structural components, thus recognizing the significant role that they play in global structural response (Baggio et al. 2007).
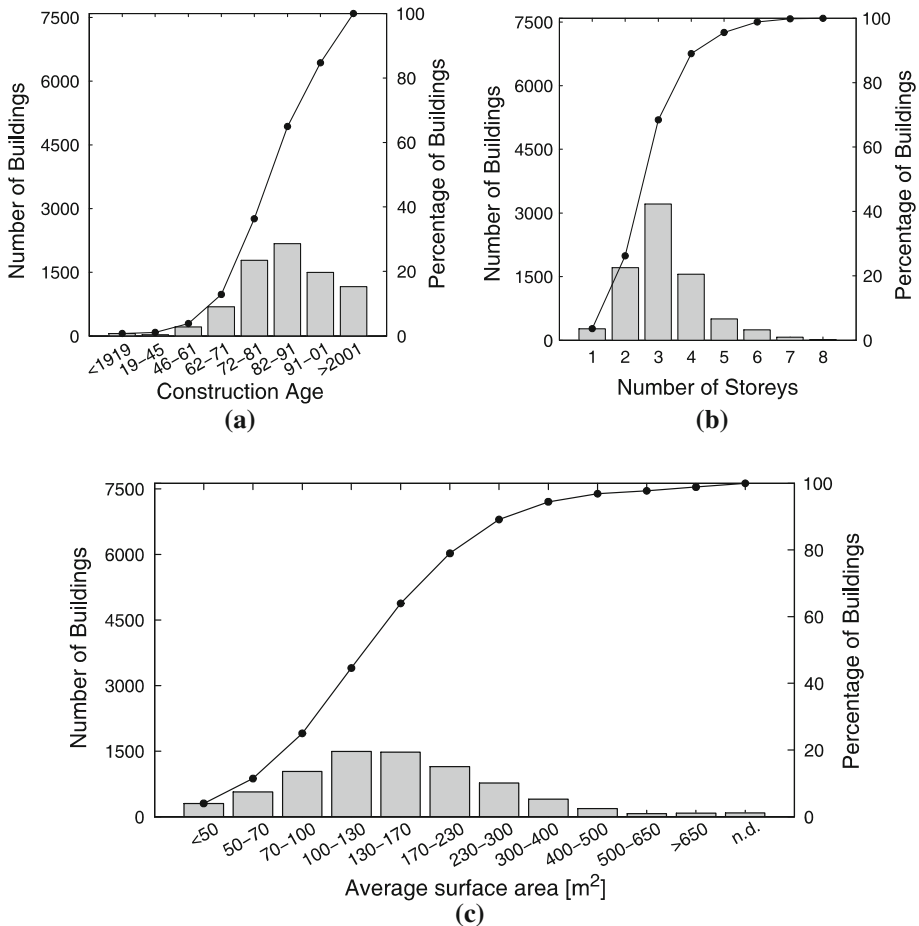
**Fig. 3** Distribution and cumulative percentage of buildings as a function of construction age (**a**), number of storeys (**b**) and average storey surface (**c**)

In details, as shown in Fig. 4, the Sect. 4 of AeDES form includes four damage levels, D, related to structural components: D0 (no damage), D1 (slight damage), D2–D3 (medium or heavy damage), and D4–D5 (very heavy or collapse). In addition, the AeDES form reports information on the damage extent on each structural component: damage extent lower than 1/3, between 1/3 and 2/3, and greater than 2/3 of the storey components (Fig. 4).

Figure 5 reports the frequency and the cumulative percentage of the buildings as a function of the damage level. In this section, the damage level to the building (D) has been defined as the heaviest damage level to single structural components, i.e. $D = \max (D_{i,j})$, with $i = 1$; $2–3$; $4–5$ and $j = 1$; 5 (structural component: Vertical Structures (VS) or Infills–Partitions (IP), i.e. URM infill walls). Indeed, the analysis of damage data demonstrates that the remaining structural components are usually not significantly damaged or less damaged than VS and IP. It is noted that the damage extent has not been taken into account to determine the building damage level D. Figure 5 shows that out of 7597 residential RC buildings, 34 % (2564 buildings) had no damage both to VS and IP, 36 %

| Level - extension | DAMAGE | | | | | | | | | |
| | D4-D5 Very heavy | | | D2-D3 Medium-severe | | | D1 Slight | | | Null |
| Structural component Pre-existing damage | $> 2/3$ | $1/3 - 2/3$ | $< 1/3$ | $> 2/3$ | $1/3 - 2/3$ | $< 1/3$ | $> 2/3$ | $1/3 - 2/3$ | $< 1/3$ | |
| | A | B | C | D | E | F | G | H | I | L |
| 1 Vertical structures | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ○ |
| 2 Floors | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ○ |
| 3 Stairs | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ○ |
| 4 Roof | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ○ |
| 5 Infills-partitions | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ○ |
| 6 Pre-existing damage | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ○ |

**Fig. 4** AeDES form: "Sect. 4—damage to the structural components" (Baggio et al. 2007)

**Fig. 5** Distribution and cumulative percentage of buildings as a function of damage level (D)
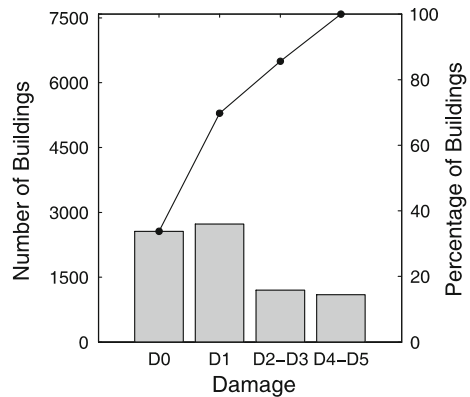


(2733 buildings) and 30 % (16 % D2–D3 and 14 % D4–D5 corresponding to 2300 buildings) showed a maximum damage grade between VS and IP equal to D1 or D2–D5, respectively.

The frequency of buildings that reached a certain damage level D (i.e. D1, D2–D3 or D4–D5) due to heaviest damage observed on IP, on VS or on IP and VS simultaneously (named IP–VS) is depicted in Fig. 6. It is shown that, for each damage level, the heaviest damage was mainly attained on IP. This clearly confirms the crucial role of IP in the damage and loss assessment. In particular, in the damage level D1, the population of 2733 buildings consisted of 2380 (87 %) buildings with a heaviest damage detected on IP, while 259 and 94 showed a heaviest damage on IP–VS or VS, respectively. The same trend can be observed for damage level D2–D3 (out of 1202 buildings, 84 % heaviest damage detected on IP) and D4–D5 (out of 1097 buildings, 67 % heaviest damage detected on IP).

The frequencies of damage level of buildings (D) are strictly related to the main parameters involving the structural seismic behaviour (i.e. in plan and elevation regularity or irregularity, type of horizontal structures, construction age, number of storeys, pre-
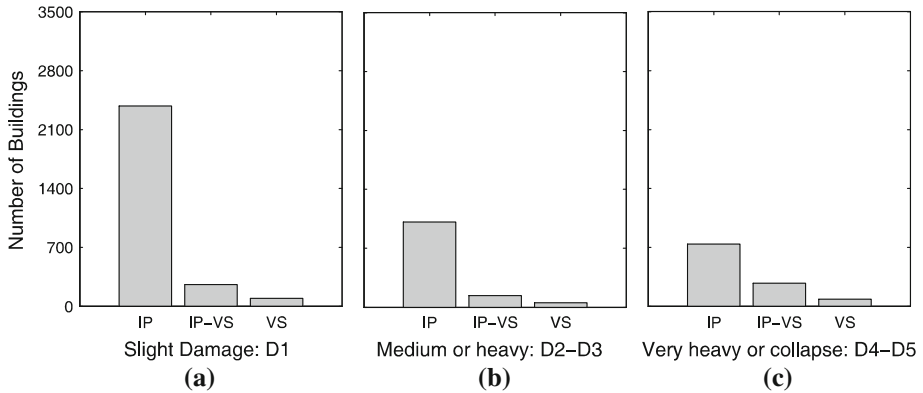
**Fig. 6** Frequency of buildings with a maximum damage on IP, IP-VS, or VS: damage level D1 (**a**), D2–D3 (**b**), and D4–D5 (**c**)

existing damage, construction quality, and previous strengthening interventions) as well as the seismic demand in terms of earthquake intensity. Thus, in Fig. 7 the frequencies of damages related to the building dataset are reported as a function of the construction age and the number of storeys which have been assumed as the most significant macro-parameters influencing the seismic structural behaviour (Rota et al. 2008). Indeed, such parameters, although definitely incomplete to assess the seismic capacity of a structure, are easily and reliably determined in the usability surveys. They provide preliminary information on the structural capacity to sustain seismic actions as widely demonstrated by several theoretical studies and observed post-earthquake damages (Rota et al. 2008; Verderame et al. 2009; Polese et al. 2015; Di Ludovico et al. 2016a, b). The percentage ratio of RC buildings, belonging to each damage level (D), for construction age and number of storeys classes of buildings, is reported in Fig. 7a, b.

Figure 7a shows that the percentage ratios of buildings with no damage (D0) have an increasing trend with more recent construction age classes (i.e. D0 involves 14 % of buildings belonging to ′46 -′61 construction age class and 49 % in >2001 construction age
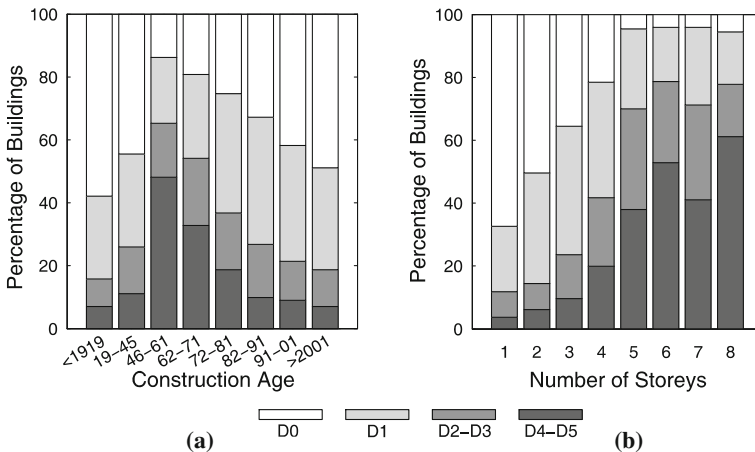


**Fig. 7** Damage level to buildings (D) as a function of construction age (**a**) and number of storeys (**b**)

class). By contrast, an opposite trend can be observed for buildings with a damage level (D4–D5); the percentage ratios of buildings with damage level (D4–D5) in ′46 -′61 construction age class is 7 times higher than that of buildings built after 1981 (48 % vs. 7 %). This trend is a clear effect of the continuous upgrade of the seismic codes and the construction practice (Dolce and Goretti 2015). Vice versa, an unexpected distribution of damage level is observed for the construction age classes (<1919) and (1919–1945), which show a relatively high percentage of buildings with no damage (D0) and low percentage of buildings with (D4–D5) damage level. Such a result can be explained, on a side, by the low statistical significance of these data, due to the very scarce population of these construction age classes, which represent the 1.1 % of the whole building population; on the other side, it has to be noted that PGA demand and number of storeys of buildings in these two classes were lower, on average, than that related to the other construction age classes (i.e. average PGA demand of 0.32 vs. 0.36 g and average number of storeys slightly less than 3 versus slightly more than 3 for buildings in construction age classes (<1919) and (1919–1945) and other classes, respectively).

The number of storeys has also affected the damage level: the lower the number of storeys, the higher the percentage ratios of buildings with no damage (D0), as shown in Fig. 7b. This trend is not confirmed for classes of buildings with more than 5 storeys which are again very poorly populated.

# 4 Definition of damage grades and building classes

In this Section, data on level and extent of damage to IP and VS components are investigated in order to derive, for each building, a damage grade (DG) according to the European Macroseismic Scale EMS-98 (Grünthal 1998), which is one of the most recognized and widespread damage scale currently used.

Criteria to derive the building DGs consistent with EMS-98 starting from observational data are illustrated in this Section; according to these DGs, the fragility curves for building classes are then determined.

In Sect. 4 of AeDES survey form, Fig. 4, four damage levels (D) are reported; as stated in (Baggio et al. 2007), the genesis and definition of damage to different structural components has been defined in accordance with the European Macroseismic Scale EMS-98 (Grünthal 1998); however, EMS-98 reports six damage grades. In (Dolce and Goretti 2015) the *condensed* damage levels D2–D3 and D4–D5 are split into the corresponding EMS-98 DGs depending on the mean damage of the building class in the selected location: the higher the mean damage, the higher the probability of being in the heaviest DG.

In the present work, the correspondence between damage level on VS and the six EMS-98 damage grades (DGs) is evaluated starting from the condensed damage of AeDES survey form. In particular, the criteria reported in (Rota et al. 2008), which is only slightly different from that one adopted by (Dolce et al. 1999), have been assumed and recalled in the first column of Table 1. In (Rota et al. 2008), in order to obtain an unambiguous criterion, the authors consider only structural damage to obtain the damage grade associated to each surveyed building. The non-structural damage is neglected, although they use the latter to separate cases of no damage from cases of incompletely filled forms.

Damage to infills–partitions (IP) is also used in this study to determine the damage grade associated to each surveyed building. In particular, the AeDES condensed damage levels for IP are converted into the EMS-98 DGs assuming an equivalence between the

**Table 1** Correspondence between DG (EMS98) and damage level described in AEDES survey form (Baggio et al., 2007) for VS and IP

| Vertical Structures | | | | Infills–Partitions | | | |
|---|---|---|---|---|---|---|---|
| EMS-98 damage | | AeDES damage | | EMS-98 damage | | AeDES damage | |
| Damage grade | Damage description | Damage level | Extent | Damage grade | Damage description | Damage level | Extent |
| DG1 | Fine cracks in plaster over frame members | D1 | <1/3 1/3–2/3 >2/3 | DG1 | Fine cracks in partitions and infills | D1 | <1/3 1/3–2/3 >2/3 |
| DG2 | Cracks in columns and beams of frames and in structural wall | D2–D3 | <1/3 | DG2 | Cracks in partitions and infills | D2–D3 | <1/3 1/3–2/3 >2/3 |
| DG3 | Cracks in columns and beam column joints of frames at the base and at joints of coupled walls. Spalling of concrete cover, buckling of reinforced rod | D2–D3 | 1/3–2/3 >2/3 | DG3 | Large cracks in partition and infill walls and failure of individual infill panels | D4–D5 | <1/3 1/3–2/3 >2/3 |
| DG4 | Large cracks in the structural elements | D4–D5 | <1/3 1/3–2/3 | | | | |
| DG5 | Destruction with collapse of ground floor/part of building | D4–D5 | >2/3 | | | | |

descriptions of the damage between the two scales, as reported in the second column of Table 1:

- The AeDES "*Slight damage*" (D1), corresponding to the first detachment of the infills–partitions from surrounding RC structure (up to 2 mm) and to a slight diagonal cracking of the infill-partition itself (<1 mm) is associated to the EMS-98 "*Negligible to slight damage*" (DG1).
- The AeDES "*Moderate to heavy damage*" (D2–D3), defined by diagonal cracks, evident crushing at the corners in contact with the bearing structures and sometimes localized failure of the infills–partitions is associated to the EMS-98 "*Moderate damage*" (DG2).
- The AeDES "*Very heavy damage*" (D4–D5), defined by large cracks in partition and infill walls, failure of individual infills–partitions, is associated to the EMS-98 "*Substantial to heavy damage*" (DG3).

Note that (D2–D3) or (D4–D5) damage level on IP may lead to building rating "unusable" which means that the building cannot be used in any of its parts. However, the aim of this work is to evaluate seismic fragility curves fully consistent with EMS-98 grades of damage to VS and IP without taking into account possible damage consequences, including usability.

Figure 8 reports example damage of EMS-98 DGs to VS and IP. In this study the heaviest DG derived separately for VS and IP is assigned to the building to determine its damage grade. In the case of no damage both to VS and IP, the DG0 is associated to the building.

Figure 9 shows DG distributions for the entire dataset previously analyzed in Sect. 3. The observed damage scenario for the whole building stock is not particularly severe. In fact, 34 % of the dataset has a "*Negligible damage*" (DG0), 36 %, 15 % and 10 % belong to "*Slight damage*" (DG1), "*Moderate damage*" (DG2) and "*Substantial to heavy damage*" (DG3) respectively, and only the 4 % and 1 % by "*Very heavy damage*" (DG4) and "*Destruction*" (DG5), respectively. As previously stated, DG4 and DG5 must be related exclusively to damage to VS, as reported in Table 1. Then, the slight to heavy damage (DG1–DG3) may be due to the corresponding damage to VS, IP or both, depending on which of the two is characterized by the heaviest damage.

Table 2 reports the number of buildings of the dataset belonging to each DG due to the corresponding damage to VS, IP or IP–VS. Table 2 shows that the damage grades, DG1, DG2 and DG3 has been mainly attained due to the damage to infills–partitions (IP). In particular, as shown in Fig. 10, on average, in 87 % of the cases the damage to IP governs the damage grade of the building; vice versa, according to Table 1, DG4 and DG5 are related exclusively to damage to VS.



**Fig. 8** EMS-98 DGs to Vertical Structures and Infills–Partitions

**Fig. 9** Distribution and cumulative percentage of buildings as a function of damage grades (DGs) defined according to Table 1
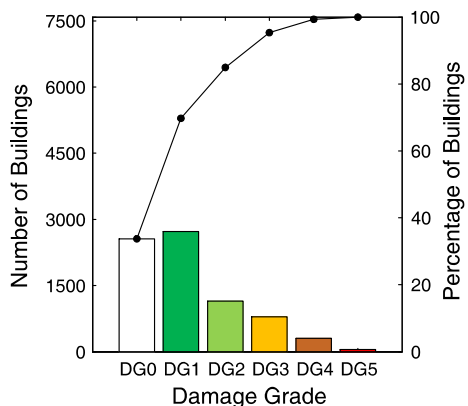
**Table 2** Number of buildings belonging to each damage grade due to IP, IP–VS or VS

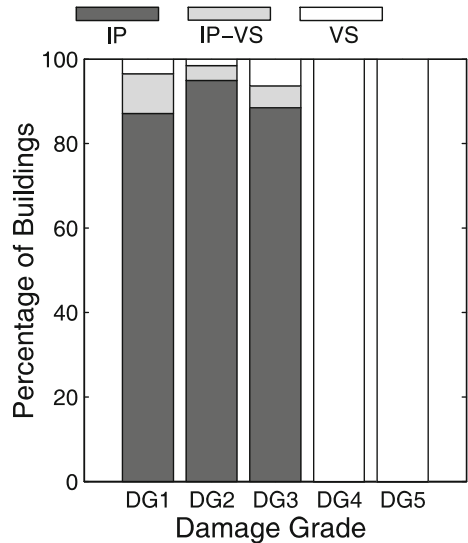|                                                          | DG0  | DG1  | DG2  | DG3 | DG4 | DG5 |
|----------------------------------------------------------|------|------|------|-----|-----|-----|
| Infills–Partitions (IP)                                  | 2564 | 2380 | 1013 | 699 | –   | –   |
| Infills–Partitions and Vertical Structures (IP–VS)       |      | 259  | 96   | 41  | –   | –   |
| Vertical Structures (VS)                                 |      | 94   | 44   | 50  | 303 | 54  |



**Fig. 10** Percentage ratio of buildings belonging to a given DG due to the maximum damage detected on VS, IP or VS–IP

Figure 11 reports the Cumulative Damage Probability Matrices (C-DPMs), defining the probabilities of reaching or exceeding a given DG, through a spatially extended grid of $10 \times 10$ km$^2$ for the RC residential building dataset. C-DPMs have been obtained cumulating from the highest to the lower DG the frequencies of buildings inside a specified grid characterized by a particular DG, i.e. the Damage Probability Matrix (DPM) for that particular grid. Obviously, in Fig. 11 the cumulative probabilities of reaching or exceeding DG0 is always equal to 100 %. Furthermore, it can be noted that the most severe DGs are attained in the grids near the epicenter, in the neighborhood of L'Aquila Municipality.

In the following C-DPMs will be presented with reference to two classes of buildings defined as a function of the *number of storeys* (N$_s$).

Generally speaking, the parameters defining building classes have to be selected based on two criteria: (1) the influence on seismic vulnerability; and (2) the availability of this kind of information when using the fragility curves for a seismic vulnerability assessment.

The number of storeys (N$_s$), together with the structural type, is relatively easy to collect and it is provided also by low-detailed sources of data (e.g., census data and usability forms). This parameter plays an essential role in defining the seismic behaviour of a structure. Typically, two (1–3; ≥4) or three (1–3; 4–7; ≥8) classes of height can be used as a function of N$_s$ for RC buildings (Rossetto and Elnashai 2003; Lagomarsino and Giovinazzi 2006; Rota et al. 2008).

Another parameter often used to define building classes is the construction age, which can be used to assess the design actions (namely gravitational or seismic) and, in the case
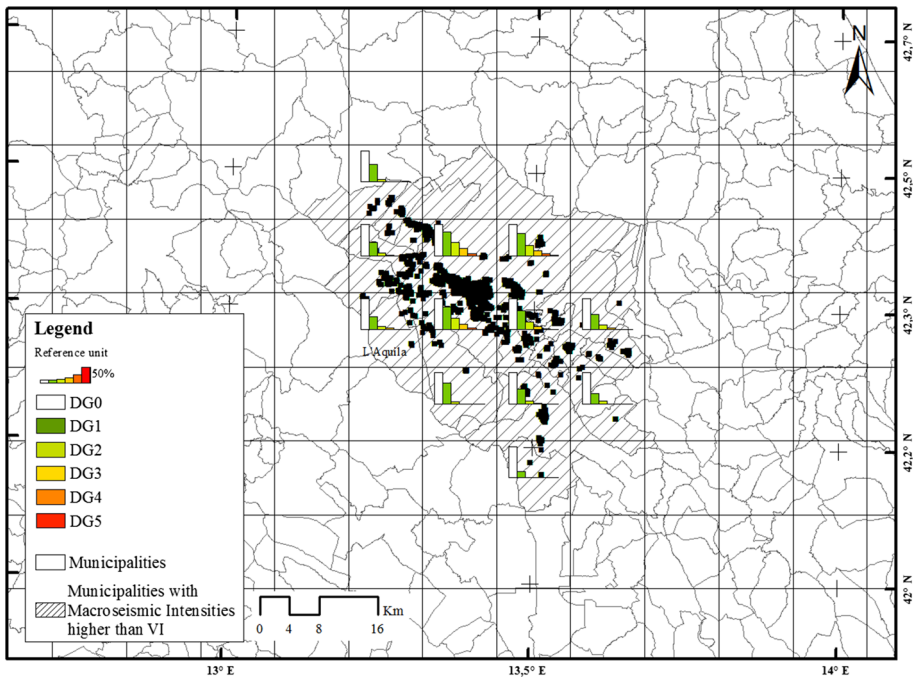
**Fig. 11** C-DPMs for $10 \times 10$ km$^2$ spatially extended grids and spatial distribution of 7597 RC buildings dataset (*black squares*)

of seismic actions, the extent of the seismic forces and code provisions regarding seismic details (e.g., longitudinal and transverse reinforcement ratio and anchorage details, transverse reinforcement in beam-column joints, etc.).

L'Aquila Municipality was firstly classified in II Seismic Category with the R.D.L. n. 431 (1927) and this classification has been confirmed until today, see (Ricci et al. 2011). Thereby, nearly all the buildings of the database have been designed for seismic loads, see Fig. 3a. The data related to damage collected by AeDES survey forms, Fig. 7a, show that—excluding the first two intervals, which are not significantly populated—the heaviest damage detected on buildings decreases for more recent buildings' construction ages without any abrupt change. Hence, it is likely to assume that the observed decrease in vulnerability is due to the continuous improvements in seismic code provisions and construction practice. The same conclusions are drawn by Dolce and Goretti (2015), on a wider database of buildings, including masonry structural type; the authors propose that all the L'Aquila buildings constructed after 1927 should belong to the same vulnerability class, namely the class "D" according to the EMS-98 classification (corresponding to "moderate level of earthquake resistant design").

Therefore, a simple subdivision depending on the number of storeys is herein carried out. Two different building classes are introduced: "L", Low rise ($1 \leq N_s \leq 3$) buildings, and "MH", Medium–High rise ($N_s \geq 4$) buildings. It has to be noted that the L class is more populated, 69 %, whereas the MH class represents the 31 % of the sample.

Figure 12 reports the C-DPMs for the two building classes and for different PGA bins, ranging from 0.10 to 0.50 g. As expected, the distribution of DGs becomes more severe with increasing PGA. Furthermore, for a given PGA bin, the distribution of the damage
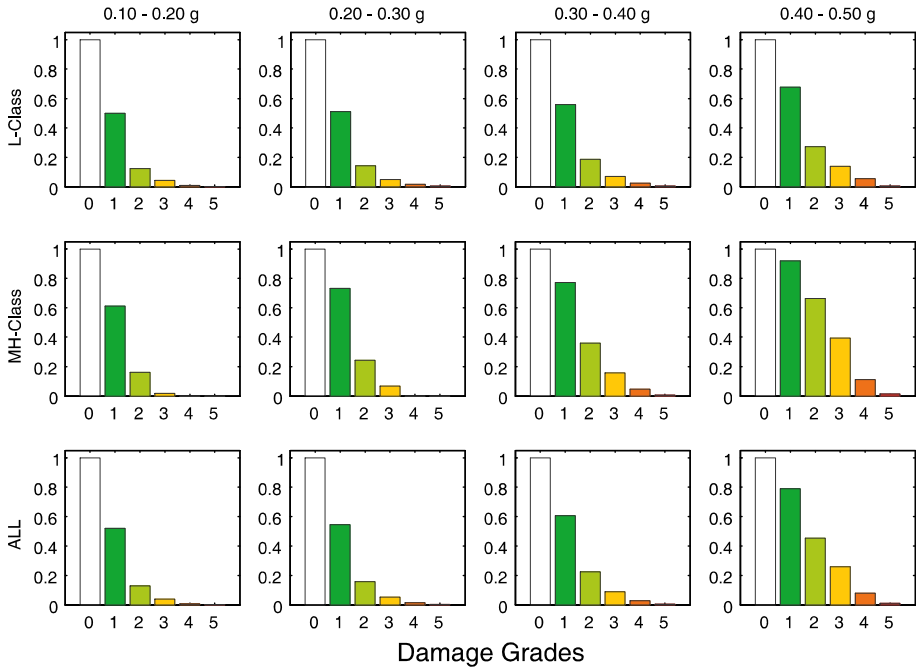
**Fig. 12** Cumulative DPMs for different building classes, "L" Low rise, "MH" Medium–High rise, "ALL", and PGA bins

results to be more severe for buildings with a higher number of storeys. Therefore, it can be inferred that the parameter adopted to define buildings classes has been properly selected as significantly influencing the seismic behaviour of buildings and correspondingly their damage. Indeed, observed damage appears to be more severe for buildings with more than 3 storeys.

# 5 Definition of fragility curves

A fragility function defines the exceeding probability of a damage grade $DG \geq dg$ as a function of a ground motion Intensity Measure (IM):

$$P[DG \geq dg | IM] \tag{1}$$

Macroseismic parameters have been adopted in the past as IMs for the derivation of fragility curves; they were the most widespread before the development of large-scale instrumental devices for earthquakes measurement. A drawback of Macroseismic IMs is that they can introduce an interdependency between the vulnerability and the IM, since the latter is obtained from the observation of earthquake effects on buildings. Secondly, Macroseismic IM is a subjective measure, which can lead to significant discrepancies depending on the sensitivity/judgment of the inspector.

Other parameters widely used to represent ground motion intensity in empirical fragility studies are Peak Ground parameters: Acceleration (PGA), Velocity (PGV) and Displacement (PGD). Rossetto (2004) retains that PGV and PGD are better correlated to observed

damage than PGA, since the latter is not related to earthquake frequency content, duration and number of cycle. On the other hand, PGV and PGD are very sensitive to record noise content and filtering process, since they are calculated through direct and double integration of accelerograms. In addition, fewer ground motion prediction equations for PGV and PGD exist than for PGA.

Several authors emphasized that elastic spectral values provide a better correlation with empirical damage data than PGA (Spence et al. 1992; Singhal and Kiremidjian 1996; Rossetto 2004). The main critique associated with the use of elastic spectral values is the determination of equivalent vibration periods. Typically, the elastic period of vibration is used to characterize the ground motion demand for all damage grade curves, e.g. Rossetto (2004) adopts empirical relationships reported in seismic building codes (CEN 2003). Nevertheless, these relationships tend to provide conservatively low values of the structural elastic period, resulting in higher spectral acceleration values and consequently in higher design forces.

Finally, the use of inelastic spectral displacement is quite uncommon. In fact, its value is not univocally derived for the different damage grades, as it is related to different ductility values, which means that the proportion of buildings in each damage grade must be determined from the different inelastic spectral displacement values. Furthermore, determination of the ductility values corresponding to the damage grades implies carrying out a pushover analysis of a building representative of the class (Rossetto et al. 2013). Further details on IM selection issues can be found in (Rossetto et al. 2013, 2014).

For these reasons, in this study the PGA is adopted as IM in the derivation of empirical fragility curves. In particular, five PGA bins, ranging from 0.1 to 0.5 g, are considered (see Sect. 3), and the IM value for the j-th bin (PGAj) is assumed equal to the mean of the lower and upper bounds of the bin.

Once the IM has been established and the corresponding probabilities have been evaluated, a regression analysis is performed for constructing the fragility curves. To this aim, the functional form and the regression technique have to be defined. The reader is referred elsewhere for a deep and detailed discussion on these topics (Ioannou et al. 2012; Rossetto et al. 2013, 2014). Herein, some of the main functional forms and regression techniques presented in literature are illustrated and applied to the database.

One of the most widely adopted functional form is the lognormal cumulative distribution function:

$$P[DG \geq dg | PGA] = \Phi\left(\frac{\ln(PGA) - \mu}{\sigma}\right) \tag{2}$$

where $\Phi(\cdot)$ is the standard normal Cumulative Distribution Function (CDF), $\mu$ is the logarithmic mean and $\sigma$ is the logarithmic standard deviation defining the lognormal distribution. Its advantages are that it is defined for positive values (corresponding to the selected IM) and returns values between 0 and 1 (corresponding to the probabilities of attaining or exceeding a damage grade), and its skewness (i.e. its asymmetry about the mean) makes it suitable for fitting data clustered around low IM values, as often occurs in fragility analysis (Rossetto et al. 2013). The parameters $\mu$ and $\sigma$ can be estimated via a nonlinear Least Squares Estimation (LSE) fitting. LSE methodology can be implemented using weights in order to attempt to account for the heteroskedasticity (non-constant variance) of the data, i.e. minimizing the weighted instead of the simple sum of the square of the errors. In this study, the number of buildings (Sabetta et al. 1998) in each isoseismic

unit (i.e. PGA bin in our case) is assumed as weight, aimed at taking into account the different reliability of the data depending on the sample size.

Another functional form used in literature, which retains the advantage of providing fragility values between 0 and 1 for IM values between 0 and $+\infty$, is the exponential model (Rossetto and Elnashai [2003](); Amiri et al. [2007]()).

$$P[DG \geq dg|PGA] = 1 - e^{-\alpha PGA^{\beta}} \qquad (3)$$

The parameters $\alpha$ and $\beta$ defining the exponential model can be derived through the nonlinear LSE methodology. Also in this case, the number of buildings in each isoseismic unit can be used as a weight in minimizing the sum of the squares of the errors.

Another way for performing fittings with any assumed functional form—lognormal cumulative distribution or exponential function, in our case—is the Maximum Likelihood Estimation (MLE) (e.g. Baker [2015]()). Whilst LSE searches for the parameter values that provide the *most accurate* description of the data, MLE searches for the parameter values that are *most likely* to have produced the data. The MLE method is applied starting from the evaluation of the number of buildings with $DG \geq dg$ ($z_j$) out of total number of buildings in that bin ($n_j$) for each jth bin and for each DG. Hence, the probability of observing $z_j$ buildings with $DG \geq dg$ for the jth bin is given by the binomial distribution (at the right of $\prod$):

$$Likelihood = \prod_{j=1}^{m} \binom{n_j}{z_j} P[DG \geq dg|PGA_j]^{n_j} \left(1 - P[DG \geq dg|PGA_j]\right)^{n_j-z_j} \qquad (4)$$

where $\prod$ denotes a product over j-values from 1 to m. The fragility function parameters are obtained by maximizing the Likelihood function.

In summary, two functional forms are assumed ("Lognormal" and "Exponential") and the following analyses are performed: (1) nonlinear LSE weighted by the number of buildings in each isoseismic unit and (2) MLE.

## 5.1 Definition of general and "class-specific" fragility curves

In this Section, fragility curves are derived according to the methodologies described above, both for the entire building dataset (named "general"), and for the subset of building classes defined in Sect. 4 (named "class-specific"), i.e. "L", Low rise ($1 \leq N_s \leq 3$), and "MH", Medium–High rise ($N_s \geq 4$), building classes.

Figure 13 shows the distribution of the buildings belonging to each class within the assumed PGA bins. A non-homogeneous distribution is observed because the maximum seismic intensity (i.e. high PGA values) was recorded on the most populated area corresponding to the center of the municipality of L'Aquila (see Fig. 1).

Figures 14 and 15 report "general" (ALL) and "class-specific" fragility curves for the defined building classes (L, MH), for the assumed functional forms and fitting methodologies. Tables 3 and 4 reports the values of the estimated parameters for each fragility curve, together with the values of the estimated median PGA capacity (PGA, in g). The latter can be easily used for a direct comparison of the estimated seismic fragilities. Due to the reduced amount of data, no reliable estimation of the fragility curves at DG5 can be provided.

First, as expected, a lower fragility is systematically observed for L-rise buildings compared to MH-rise buildings.
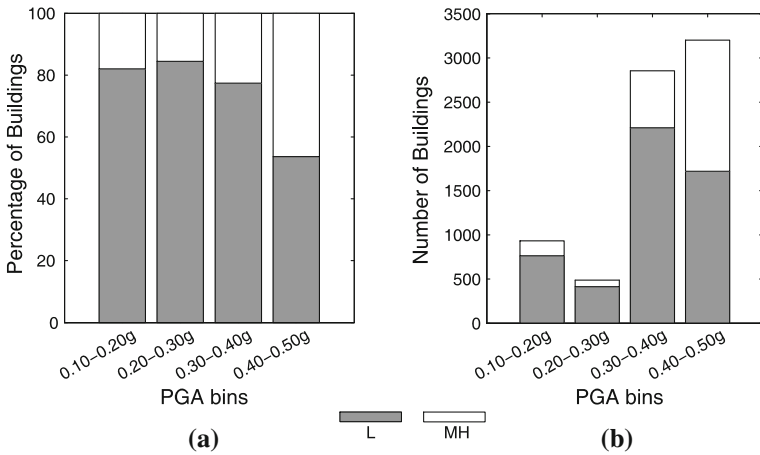
**Fig. 13** Distribution of 7597 RC buildings of L'Aquila area for building classes and PGA bins
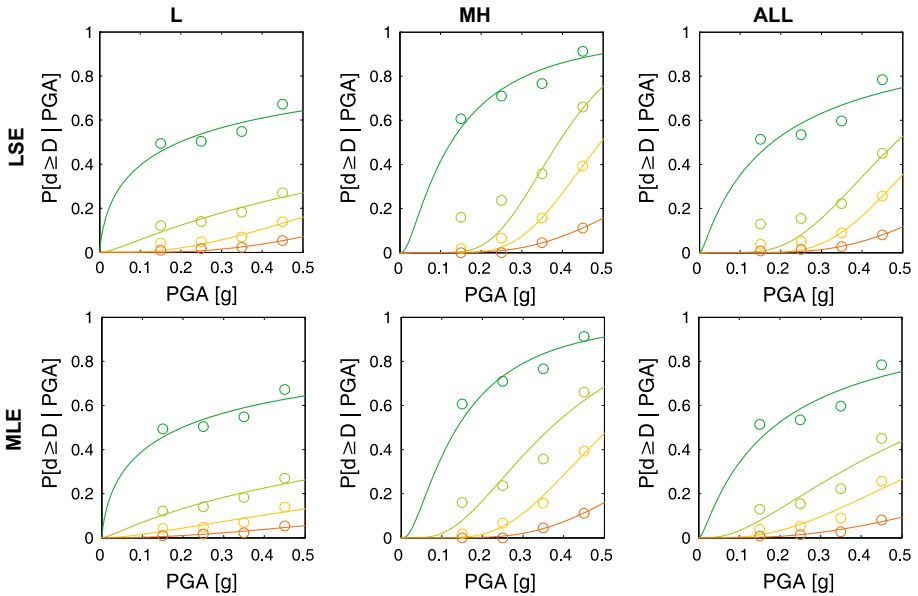


**Fig. 14** Lognormal fragility curves (*solid lines*) fitting observed fragility data (*circles*) for the assumed building classes (L, MH and ALL) and the adopted regression techniques (LSE and MLE)

As shown in Figs. 14 and 15, no significant difference is observed if the lognormal or the exponential models are used, given equal the adopted fitting methodology. Strictly speaking, the advantages of using a functional form instead of the other can be evaluated comparing the values of: (1) weighted sum of the square of the errors, in LSE methodology; and (2) Likelihood, in MLE methodology, obtained adopting the lognormal and the exponential model. In both cases, the use of the exponential model yields slightly better results, i.e. lower weighted sum of the square of the errors (in LSE methodology) and higher Likelihood (in MLE methodology).
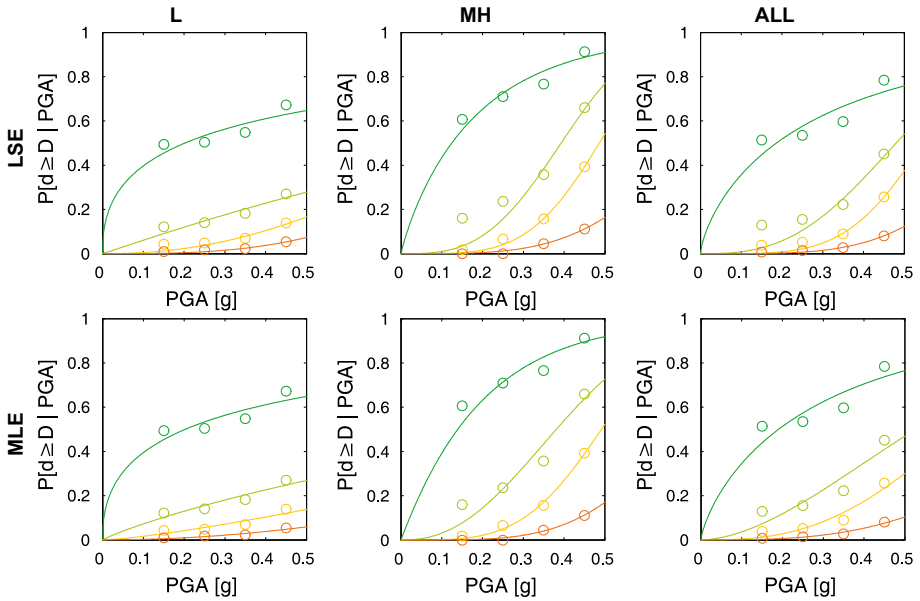
**Fig. 15** Exponential fragility curves (*solid lines*) fitting observed fragility data (*circles*) for the assumed building classes (L, MH and ALL) and the adopted regression techniques (LSE and MLE)

**Table 3** Lognormal fragility curves parameters

|      | DG1 | | | DG2 | | | DG3 | | | DG4 | | |
|------|-------|------|------|-------|------|------|-------|------|------|-------|------|------|
|      | μ     | σ    | PGA  | μ     | σ    | PGA  | μ     | σ    | PGA  | μ     | σ    | PGA  |
| LSE  |       |      |      |       |      |      |       |      |      |       |      |      |
| L    | −1.62 | 2.55 | 0.20 | 0.33  | 1.67 | 1.39 | 0.18  | 0.87 | 1.19 | 0.36  | 0.72 | 1.44 |
| MH   | −2.07 | 1.07 | 0.13 | −0.94 | 0.36 | 0.39 | −0.70 | 0.35 | 0.49 | −0.17 | 0.52 | 0.84 |
| ALL  | −1.72 | 1.53 | 0.18 | −0.73 | 0.47 | 0.48 | −0.55 | 0.37 | 0.58 | −0.10 | 0.50 | 0.91 |
| MLE  |       |      |      |       |      |      |       |      |      |       |      |      |
| L    | −1.62 | 2.51 | 0.20 | 0.53  | 1.92 | 1.69 | 1.07  | 1.57 | 2.90 | 1.33  | 1.27 | 3.79 |
| MH   | −1.98 | 0.96 | 0.14 | −1.00 | 0.64 | 0.37 | −0.66 | 0.44 | 0.51 | −0.21 | 0.48 | 0.81 |
| ALL  | −1.70 | 1.46 | 0.18 | −0.54 | 0.95 | 0.58 | −0.22 | 0.75 | 0.80 | 0.35  | 0.79 | 1.43 |

With regard to the fitting methodology, the LSE methodology leads to fragility curves relatively more conditioned by data corresponding to PGA > 0.30 g, due to the assumption on the adopted weights. The rapid increase in fragility observed in this PGA range leads to steeper curves, compared to the MLE methodology, with quite significant differences, especially at DG2 and DG3.

## 5.2 Comparison with fragility curves from literature

In the following, the fragility curves evaluated adopting the exponential functional form, through the MLE method, are compared with fragility curves proposed by other authors in literature, see Fig. 16.

**Table 4** Exponential fragility curves parameters

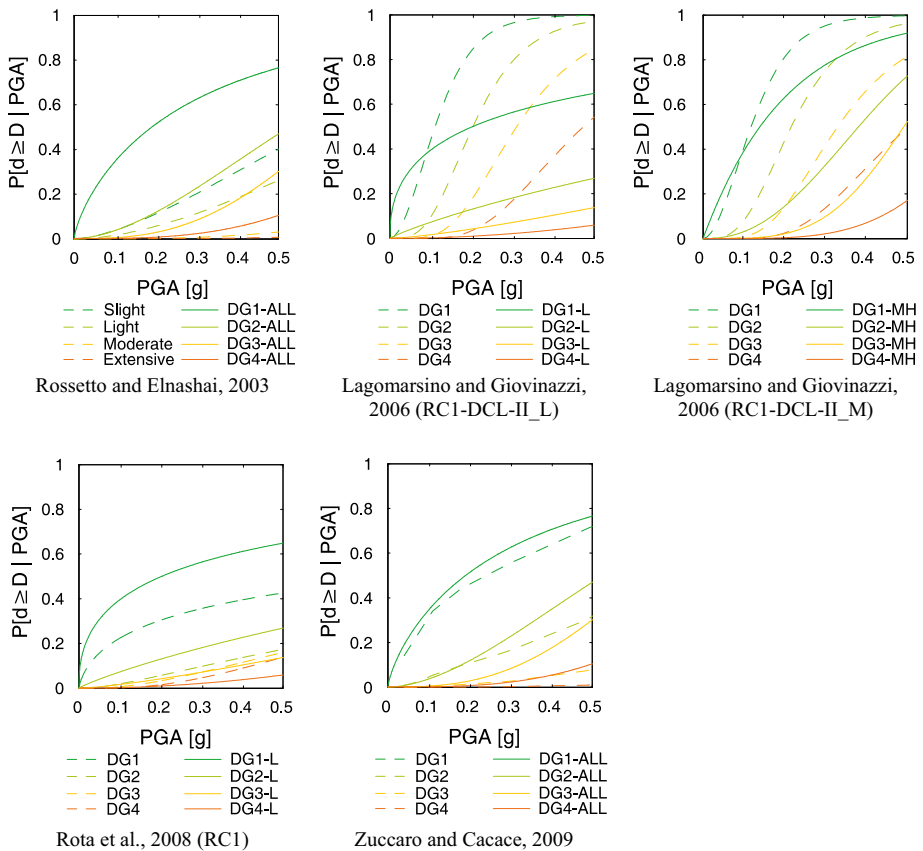|  | DG1 | | | DG2 | | | DG3 | | | DG4 | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
|  | α | β | PGA | α | β | PGA | α | β | PGA | α | β | PGA |
| LSE | | | | | | | | | | | | |
| L | 1.42 | 0.45 | 0.20 | 0.66 | 1.02 | 1.05 | 0.84 | 2.22 | 0.92 | 0.66 | 3.11 | 1.02 |
| MH | 4.46 | 0.89 | 0.12 | 12.64 | 3.11 | 0.39 | 14.57 | 4.22 | 0.49 | 2.61 | 3.87 | 0.71 |
| ALL | 2.35 | 0.73 | 0.19 | 5.41 | 2.80 | 0.48 | 9.95 | 4.40 | 0.55 | 2.46 | 4.23 | 0.74 |
| MLE | | | | | | | | | | | | |
| L | 1.43 | 0.46 | 0.20 | 0.58 | 0.89 | 1.23 | 0.38 | 1.36 | 1.56 | 0.24 | 2.01 | 1.68 |
| MH | 5.06 | 1.01 | 0.14 | 6.43 | 2.31 | 0.38 | 10.59 | 3.84 | 0.49 | 3.43 | 4.20 | 0.68 |
| ALL | 2.46 | 0.76 | 0.19 | 2.15 | 1.76 | 0.53 | 2.46 | 2.78 | 0.63 | 0.95 | 3.12 | 0.90 |



**Fig. 16** Comparison between empirical fragility curves for RC buildings proposed herein (*solid lines*) and by literature studies (*dashed lines*)

The aim is to support the reliability of the obtained results and to discuss possible differences. To this aim, we consider the main literature studies providing empirical fragility curves for RC buildings based on the same damage grades adopted herein, i.e. EMS-98 DGs, in order to compare homogeneous damage predictions. Therefore, the following studies are considered.

Rossetto and Elnashai (2003) derived observational-based vulnerability curves for European RC structures from a large database of post-earthquake damage distributions, from 19 events, including non-European earthquakes. In particular, "homogeneous" vulnerability curves are proposed, which are applicable to different RC structural systems, according to a new damage scale proposed by the authors ("HRC"). For non-ductile RC MRFs and infilled RC frames the HRC damage grades "Slight", "Light", "Moderate" and "Extensive" roughly correspond to EMS-98 DG1, DG2, DG3 and DG4. The fragility curves proposed by the authors have to be compared with the fragility curves derived herein for the "ALL" class.

Lagomarsino and Giovinazzi (2006) derived fragility curves for different building types and sub-types from the DPMs implicitly defined by EMS-98. In particular, curves for Low- and Medium-Rise Concrete Moment Resisting Frames with Earthquake Resistant Design in second seismic category with Low Ductility are reported (RC1-DCL-II_L and RC1-DCL-II_M), to be compared with the fragility curves derived herein for the "L" and "MH" classes, respectively.

The comparison with the studies by Rota et al. (2008) and Zuccaro et al. (2009) are particularly interesting, since these works were based only on damage data from Italian earthquakes.

Rota et al. (2008) provided fragility curves for several building types based on damage data from past Italian earthquakes and on EMS-98 damage scale. Four classes were proposed for RC buildings, depending on the number of storeys ($N_s \leq 3$ and $N_s \geq 4$) and on the type of design: the authors assumed that only buildings constructed after 1975 in a Municipality classified as seismic could be considered seismically designed. Due to the reduced amount of data, no fragility curve was provided for RC buildings with $N_s \geq 4$ and with seismic design. Hence, the fragility curves derived herein for the "L" class are compared with the fragility curves provided by Rota et al. (2008) for RC buildings with seismic design and $N_s \leq 3$ ("RC1" class). The latter was populated by slightly less than 2000 buildings, mainly characterized by a PGA demand <0.30 g, as deduced by (Rota et al. 2008). Note that the authors accounted only for damage to VS when determining the DG.

Zuccaro and Cacace (2009) proposed DPMs based on EMS-98 damage scale from empirical damage data on Italian earthquakes, for the EMS-98 vulnerability classes, depending on $I_{MCS}$ intensity. Within authors' database, classes from A to D were assigned to masonry buildings, and from C to D to RC buildings. Specific information about the distribution of buildings with different structural typology within the classes and, specifically, regarding the RC buildings with seismic design was not reported. Thus, in order to carry out a comparison with the fragility curves proposed herein, the following assumptions are made: (1) adoption of vulnerability class D, consistent with (Dolce and Goretti 2015); (2) correlation between PGA and $I_{MCS}$ based on the relationship by Margottini et al. (1992), as in (Zuccaro 2004). Unfortunately, it was not possible to assign to each building of the database an $I_{MCS}$ intensity value in order to derive the corresponding DPMs to be compared with Zuccaro and Cacace's (2009) proposal; hence, a theoretically equivalent comparison is carried out using this (necessarily approximate) relationship in order to

translate the $I_{MCS}$ intensity into the corresponding PGA, thus allowing a comparison with the PGA-based fragility curves proposed herein.

Figure 16 shows that Rossetto and Elnashai (2003) fragility curves (dashed lines) show a rather lower fragility at all DSs compared to those proposed herein (solid lines). The fragility curves provided by Lagomarsino and Giovinazzi (2006) for Low- and Medium-Rise buildings are very similar to each other; in the former case, a significantly higher fragility is observed.

The fragility curves provided by Rota et al. (2008) show a quite similar shape compared to the fragility curves proposed herein for the "L" class, but a lower fragility at DG1 and DG2 and a higher fragility at DG3 and DG4. The former could be explained by the damage to IP, which are not accounted for by the authors (Del Gaudio et al. 2016).

A good agreement (the best among the considered studies) is observed with the fragility curves derived from the DPMs proposed by Zuccaro and Cacace (2009), at all DGs. A relatively better agreement is thereby observed with the fragility curves proposed by the two latter studies, which are based on observational data from Italian earthquakes.

# 6 Conclusions

In this study, a database of 7597 residential RC buildings subjected to the 2009 L'Aquila earthquake has been analyzed. The data have been collected by the Italian Department of Civil Protection through survey forms aimed at evaluating building usability in the post-earthquake. The database includes information on building characteristics and level and extent of damage to structural and non-structural components. In particular, the attention has been focused on damage to Vertical Structures and Infills–Partitions components. Single building data are geo-referenced and the Peak Ground Acceleration (PGA) demand is evaluated through the ShakeMap of the event.

The database consists of 87 % of buildings built after 1970, and 85 % of buildings with a number of storeys between 2 and 4. The damage data showed that Infills–Partitions represent the most damaged component. The analysis related to level and extent of damage to Infills–Partitions and Vertical Structures components has been carried out in order to derive, for each building, a damage grade according to the European Macroseismic Scale EMS-98. The damage grades have been analyzed for two different building classes, defined as a function of number of storeys. Damage distribution has been investigated deriving Damage Probability Matrices (DPMs) for PGA bins from 0.10 to 0.50 g. Damage distribution frequencies pointed out that the most severe damage was detected on buildings with a higher number of storeys.

Fragility curves for the defined building classes—as a function of the number of storeys—and damage grades have been derived, adopting different functional forms, namely Lognormal cumulative distribution and Exponential functions, and different methodologies, which have been briefly described, namely weighted Least Squares Estimation and Maximum Likelihood Estimation methods. The results have been compared, in terms of both estimated median PGA capacity and curves shape. Finally, the proposed fragility curves have been compared with main empirical fragility curves for RC buildings from literature studies.

Based on the analyzed data, it has been observed that the influence of the construction age on the seismic behaviour of buildings can be explained by a continuous upgrade of the seismic codes and the construction practice, without any abrupt change, likely because

L'Aquila and its neighborhood were classified as seismic since 1927 and—therefore—nearly all the buildings of the database were designed for seismic loads. Hence, in the derivation of fragility curves no distinction has been made based on the construction age for the definition of building classes. On the contrary, the clear influence of building height has been observed and used to define different building classes in fragility curves evaluation.

Based on the comparison with other empirical studies from literature, it can be concluded that the response of the RC buildings subjected to L'Aquila earthquake is in acceptable agreement (however falling within the predicted range) with studies based on observational data from Italian earthquakes.

Starting from a critical review of DPMs, fragility curves and vulnerability classes or structural typologies proposed in literature, it can be highlighted that the fragility curves proposed herein can provide useful insights into the seismic fragility assessment of typical Italian existing RC buildings (especially for those designed with obsolete seismic code provisions), because they are derived:

(1)  from a subset of 7597 MRF residential RC buildings, wider than the database presented in the recent literature studies based on observational data from Italian earthquakes;
(2)  based on a relatively wide range of intensities, although from a single event;
(3)  taking into account the damage not only to Vertical Structures but also to Infills–Partitions components, which resulted to play a key role to determine the MRF infilled RC buildings global structural response and damage and loss assessment.

The fragility estimation carried out in this study can support a seismic fragility assessment aimed at risk analysis at urban and regional scale for a RC building stock with similar characteristics, i.e. for instance in seismic prone areas within Mediterranean region.

# References

Ambraseys NN, Simpson KA, Bommer JJ (1996) Prediction on horizontal response spectra in Europe. Earthq Eng Struct Dyn 25(4):371–400

Amiri GG, Jalalian M, Amrei SAR (2007) Derivation of vulnerability functions based on observational data for Iran. In: Proceedings of international symposium on innovation and sustainability of structures in civil engineering, Tongji University, China

Baggio C, Bernardini A, Colozza R, Coppari S, Corazza L, Della Bella M, Di Pasquale G, Dolce M, Goretti A, Martinelli A, Orsini G, Papa F, Zuccaro G (2007) Field manual for post-earthquake damage and safety assessment and short term countermeasures (Pinto A, Taucer F eds), Translation from Italian: Goretti A, Rota M, JRC Scientific and technical reports, EUR 22868 EN-2007

Baker JW (2015) Efficient analytical fragility function fitting using dynamic structural analysis. Earthq Spectra 31(1):579–599

Bommer JJ, Elnashai AS, Weir AG (2000) Compatible acceleration and displacement spectra for seismic design codes. In: Proceedings of the 12th world conference on earthquake engineering, Auckland, New Zeland, paper no. 207.2000

Borzi B, Pinho R, Crowley H (2008) Simplified pushover-based vulnerability analysis for large scale assessment of RC buildings. Eng Struct 30(3):804–820

Braga F, Dolce M, Liberatore D (1982) A statistical study on damaged buildings and an ensuing review of the MSK-76 scale. In: Proceedings of the 7th European conference on earthquake engineering, Athens, Greece, pp 431–450

Calvi GM (1999) A displacement-based approach for vulnerability evaluation of classes of buildings. J Earthq Eng 3(3):411–438

CEN (2003) Eurocode 8: design of structures for earthquake resistance—Part 1: general rules, seismic actions and rules for buildings. Comité Européen de Normalisation, Brussels

Cosenza E, Manfredi G, Polese M, Verderame GM (2005) A multi-level approach to the capacity assessment of existing RC buildings. J Earthq Eng 9(1):1–22

Crowley H, Pinho R, Bommer JJ (2004) A probabilistic displacement-based vulnerability assessment procedure for earthquake loss estimation. Bull Earthq Eng 2(2):173–219

De Luca F, Verderame GM, Manfredi G (2015) Analytical versus observational fragilities: the case of Pettino (L'Aquila) damage data database. Bull Earthq Eng 13(4):1161–1181

Del Gaudio C, Ricci P, Verderame GM, Manfredi G (2015) Development and urban-scale application of a simplified method for seismic fragility assessment of RC buildings. Eng Struct 91:40–57. doi:10.1016/j.engstruct.2015.01.031

Del Gaudio C, Ricci P, Verderame GM, Manfredi G (2016) Observed and predicted earthquake damage scenarios: the case study of Pettino (L'Aquila) after the 6th April 2009 event. Bull Earthq Eng. doi:10.1007/s10518-016-9919-2

Di Ludovico M, Prota A, Moroni C, Manfredi G, Dolce M (2016a) a, "Reconstruction process of damaged residential buildings outside the historical centres after L'Aquila earthquake—part I: "light damage" reconstruction. Bull Earthq Eng. doi:10.1007/s10518-016-9877-8

Di Ludovico M, Prota A, Moroni C, Manfredi G, Dolce M (2016b) b. Reconstruction process of damaged residential buildings outside historical centres after the L'aquila earthquake—part II: "heavy damage" reconstruction. Bull Earthq Eng. doi:10.1007/s10518-016-9979-3

Dolce M, Goretti A (2015) Building damage assessment after the 2009 Abruzzi earthquake. Bull Earthq Eng 13(8):2241–2264

Dolce M, Masi A, Goretti A (1999) Damage to buildings due to 1997 Umbria–Marche earthquake. In: Bernardini A (ed) Seismic damage to masonry buildings. Balkema, Rotterdam

Goretti A, Di Pasquale G (2004) Building inspection and damage data for the 2002 Molise, Italy earthquake. Earthq Spectra 20(S1):167–190

Grünthal G (1998) Cahiers du Centre Européen de Géodynamique et de Séismologie: volume 15—European Macroseismic Scale 1998. European Center for Geodynamics and Seismology, Luxembourg

Iervolino I, Manfredi G, Polese M, Verderame GM, Fabbrocino G (2007) Seismic risk of R.C. building classes. Eng Struct 29(5):813–820

Ioannou I, Rossetto T, Grant DN (2012) Use of regression analysis for the construction of empirical fragility curves. In: Proceedings of the 15th world conference on earthquake engineering, September 24—28, Lisbon, Portugal. Paper 2143

ISTAT (2011) 15° Censimento della popolazione e delle abitazioni 2011. Istituto Nazionale di Statistica. http://www.istat.it/it/censimento-popolazione/censimento-popolazione-2011

Lagomarsino G, Giovinazzi S (2006) Macroseismic and mechanical models for the vulnerability and damage assessment of current buildings. Bull Earthq Eng 4:415–443

Liel A, Lynch K (2012) Vulnerability of reinforced-concrete-frame buildings and their occupants in the 2009 L'Aquila, Italy, earthquake. Nat Hazards Rev 13(1):11–23

Margottini C, Molin D, Serva L (1992) Intensity versus ground motion: a new approach using Italian data. Eng Geol 33(1):45–58

Medvedev SV (1977) Seismic Intensity Scale MSK-76. Publication Institute of Geophysics of Poland, Academy of Sciences, Varsaw

Michelini A, Faenza L, Lauciani V, Malagnini L (2008) ShakeMap implementation in Italy. Seismol Res Lett 79(5):688–697

Orsini G (1999) A model for buildings' vulnerability assessment using the Parameterless Scale of Seismic Intensity (PSI). Earthq Spectra 15(3):463–483

Polese M, Di Ludovico M, Marcolini M, Prota A, Manfredi G (2015) Assessing reparability: simple tools for estimation of costs and performance loss of earthquake damaged reinforced concrete buildings. Earthq Eng Struct Dyn 44(10):1539–1557

Regio Decreto Legge n. 431 del 13/3/1927 (1927) Norme tecniche ed igieniche di edilizia per le località colpite dai terremoti. G.U. n. 82 dell'8/4/1927 **(in Italian)**

Regio Decreto Legge n. 573 del 29/4/1915 (1915) Che riguarda le norme tecniche ed igieniche da osservarsi per i lavori edilizi nelle località colpite dal terremoto del 13 gennaio 1915. G.U. n. 117 dell'11/5/1915 **(in Italian)**

Ricci P, De Luca F, Verderame GM (2011) 6th April 2009 L'Aquila earthquake, Italy: reinforced concrete building performance. Bull Earthq Eng 9(1):285–305

Rossetto T (2004) Vulnerability curves for the seismic assessment of reinforced concrete structure populations. PhD Thesis, Imperial College, London, UK

Rossetto T, Elnashai A (2003) Derivation of vulnerability functions for European-type RC structures based on observational data. Eng Struct 25(10):1241–1263

Rossetto T, Ioannou I, Grant DN (2013) Existing empirical fragility and vulnerability functions: compendium and guide for selection. GEM technical report 2013-X, GEM Foundation, Pavia

Rossetto T, Ioannou I, Grant DN, Maqsood T (2014) Guidelines for empirical vulnerability assessment. GEM Technical Report 2014-X, GEM Foundation, Pavia

Rota M, Penna A, Strobbia CL (2008) Processing Italian damage data to derive typological fragility curves. Soil Dyn Earthq Eng 28(10):933–947

Sabetta F, Goretti A, Lucantoni A (1998) Empirical fragility curves from damage surveys and estimated strong ground motion. In: Proceedings of the 11th European conference on earthquake engineering, Paris, France, September 6–11

Sieberg A (1930) Geologie der Erdbeben. Handbuch der Geophysik 2(4):552–555

Singhal A, Kiremidjian AS (1996) Method for probabilistic evaluation of seismic structural damage. ASCE J Struct Eng 122(12):1459–1467

Spence RJS, Coburn AW, Sakai S, Pomonis A (1991) A parameterless scale of seismic intensity for use in the seismic risk analysis and vulnerability assessment. In: International conference on earthquake, blast and impact, Manchester, UK, September 19–20, pp 19–30

Spence RJS, Coburn AW, Pomonis A (1992) Correlation of ground motion with building damage: the definition of a new damage-based seismic intensity scale. In: Proceedings of 10th world conference on earthquake engineering, Balkema, Rotterdam

Verderame G, Iervolino I, Ricci P (2009) Rapporto fotografico dei danni subiti dagli edifici a seguito dell'evento sismico del 6 aprile 2009 ore 1.32 (utc) – aquilano. Available at http://www.reluis.it (in Italian)

Verderame GM, De Luca F, Ricci P, Manfredi G (2011) Preliminary analysis of a soft-storey mechanism after the 2009 L'Aquila. Earthqu Eng Struct Dyn 40:925–944

Verderame GM, Ricci P, De Luca F, Del Gaudio C, De Risi MT (2014) Damage scenarios for RC buildings during the 2012 Emilia (Italy) earthquake. Soil Dyn Earthq Eng 66:385–400

Wald DJ, Worden CB, Quitoriano V, Pankow KL (2006) ShakeMap® Manual, technical manual, users guide, and software guide. http://pubs.usgs.gov/tm/2005/12A01/pdf/508TM12-A1.pdf

Zuccaro G (2004) Progetto SAVE—Task1: inventario e vulnerabilità del patrimonio edilizio residenziale del territorio nazionale, mappe di rischio e perdite socio-economiche. INGV/GNDT (in Italian)

Zuccaro G, Cacace F (2009) Revisione dell'inventario a scala nazionale delle classi tipologiche di vulnerabilità ed aggiornamento delle mappe nazionali di rischio sismico. Atti del XIII Convegno ANIDIS "L'ingegneria sismica in Italia", June 28–July 2, Bologna, Italy. Paper S14.39 (in Italian)

Zuccaro G, Cacace F (2015) Seismic vulnerability assessment based on typological characteristics. The first level procedure "SAVE". Soil Dyn Earthq Eng 69:262–269