



DERIVATION OF FRAGILITY CURVES FOR ITALIAN RC BUILDINGS FROM POST-EARTHQUAKE DAMAGE DATA

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Abstract

This paper presents the derivation of empirical fragility curves for the residential reinforced concrete building stock, by taking advantage of post-earthquake damage data collected by the Italian Department of Civil Protection after the major Italian earthquakes occurred in the last 50 years. Reinforced concrete buildings are first classified into fifteen structural typologies, based on the number of stories and type of design. Typological fragility curves are derived, as a function of the peak ground acceleration, by considering five damage states based on the EMS-98 classification and by accounting for damage on both structural and non-structural building components. Observational data are fitted by lognormal cumulative curves through the maximum likelihood estimate approach, using the multinomial distribution to subdivide the number of buildings in the different damage states. To make the proposed fragility model easily usable for territorial seismic vulnerability and risk applications based on poor census data, building typologies are aggregated into two vulnerability classes (i.e. C2 and D), of decreasing vulnerability. Vulnerability class C2 groups buildings designed for gravity loads only and for seismic loads pre-1981, whilst vulnerability class D refers to buildings designed for seismic loads post-1981. Empirical fragility curves are derived for predefined vulnerability classes and classes of building height (i.e. low-rise, mid-rise and high-rise), by suitably averaging typological fragility curves. An example of application is also presented, to show the feasibility of the proposed fragility model for large-scale seismic risk evaluations.

Keywords: seismic vulnerability, empirical fragility curves, post-earthquake damage data, RC buildings, seismic risk



1. Introduction

Depending on the nature of the available data and purpose of the study, different methods can be adopted for assessing seismic vulnerability. Empirical approaches exploit damage data from past earthquakes, collected during field inspections, to derive either Damage Probability Matrices (DPMs) or fragility curves. For a given building typology, Damage Probability Matrices represent the damage distribution conditioned on a given intensity level (e.g. [1], [2], [3]), whereas fragility curves express the probability of reaching or exceeding different damage levels, as a function of the ground shaking (e.g. [4], [5], [6], [7]).

Several sources of uncertainty, associated with the acquired data and typically driven by survey conditions (e.g. [6]), can affect the credibility of observational damage data. Nevertheless, if carefully processed and interpreted, post-earthquake data can be an invaluable source of information on the seismic vulnerability of the existing building stock, which can be also exploited for testing the predictive capability of fragility curves derived through alternative methods (e.g. [8]). Furthermore, given their statistical nature, empirical approaches are more appropriate for large-scale evaluations, rather than for the assessment of single buildings (e.g. [2], [9], [10], [11]).

In this work, empirical fragility curves for residential RC buildings are derived, by statistically processing observational damage data of Italian seismic events of the period 1980-2009 (Section 2). The peak ground acceleration (PGA) is selected to represent the ground shaking experienced at the different building locations and RC buildings are classified into different building typologies, based on the number of stories (from 1 to 5) and design level (i.e. gravitational, seismic pre-81 and seismic pre-81). Starting from the damage description available from the post-earthquake survey forms, a global level of damage is attributed to each inspected building, by suitably accounting for both structural and non-structural damage. Typological fragility curves are derived by fitting the cumulative lognormal distribution to observational data points via the maximum likelihood estimate approach. Two vulnerability classes of decreasing vulnerability (i.e. C2 and D) are defined, starting from the typological classification of the RC building stock. Fragility curves are hence derived for vulnerability classes and classes of building height, by suitably averaging typological fragility curves, based on their diffusion at the national scale, evaluated through census data (Section 3). The proposed fragility model is compatible with the main characteristics of the Italian national seismic risk platform ([12], <http://irma.eucentre.it/irma/web/home>), where it was implemented to carry out the case-study application presented in Section 4.

2. The post-earthquake damage database

Fragility curves are derived by statistical elaboration of empirical damage data available in the Da.D.O. platform [13], collecting post-earthquake damage data of the main Italian earthquakes occurred from 1976 to 2012 (i.e. Friuli 1976, Irpinia 1980, Abruzzo 1984, Umbria-Marche 1997, Pollino 1998, Molise 2002, Emilia 2003, L'Aquila 2009, Emilia 2012). The Da.D.O. platform includes 319'470 survey forms, about 78% of which refers to masonry buildings, 8% to RC buildings and 14% to other building typologies.

In this study, the damage databases of the 1980 Irpinia and of the 2009 L'Aquila seismic events (Fig. 1) are employed, given the availability of shakemaps, consistently defined and used for ground motion characterization, and the availability of complete post-earthquake surveys. The incompleteness of post-earthquake surveys is indeed a critical issue of empirical fragility evaluations [6] and it arises when field surveys are carried out on request of the building owner only. As a consequence, the survey is incomplete and typically limited to damaged buildings. In these cases, the resulting damage distributions may be biased by the fact that the number of undamaged buildings is underestimated. This issue is more significant in the territories less affected by the earthquake, where it is very likely that non-inspected buildings were not surveyed because undamaged.

All the municipalities of the Irpinia database were completely surveyed [1]. After the L'Aquila event, the survey of residential buildings was instead carried out building by building in the municipalities with felt macroseismic intensity higher than VI (MCS) and only under request in all the other cases [14]. In this work,



the L'Aquila completely surveyed municipalities were identified based on a completeness threshold of 90% (Fig. 1). In other words, the municipalities with completeness ratio (i.e. number of inspected buildings over the total number of buildings, evaluated from national census [15]) exceeding 90% were considered to be completely surveyed. The resulting post-earthquake damage dataset counted more than 10'000 RC buildings.

In accordance with other literature studies (e.g. [16]), the negative evidence of damage in the municipalities less affected by the ground shaking was accounted for by integrating the available post-earthquake damage dataset by undamaged buildings located in the Abruzzi non-surveyed and partially-surveyed (with completeness ratio lower than 10%) municipalities. In particular, 176 municipalities were not surveyed, whereas 49 municipalities were characterized by a completeness ratio lower than 10%. The number of RC buildings sited in these municipalities was retrieved from national census [15] and added to the database as undamaged buildings.

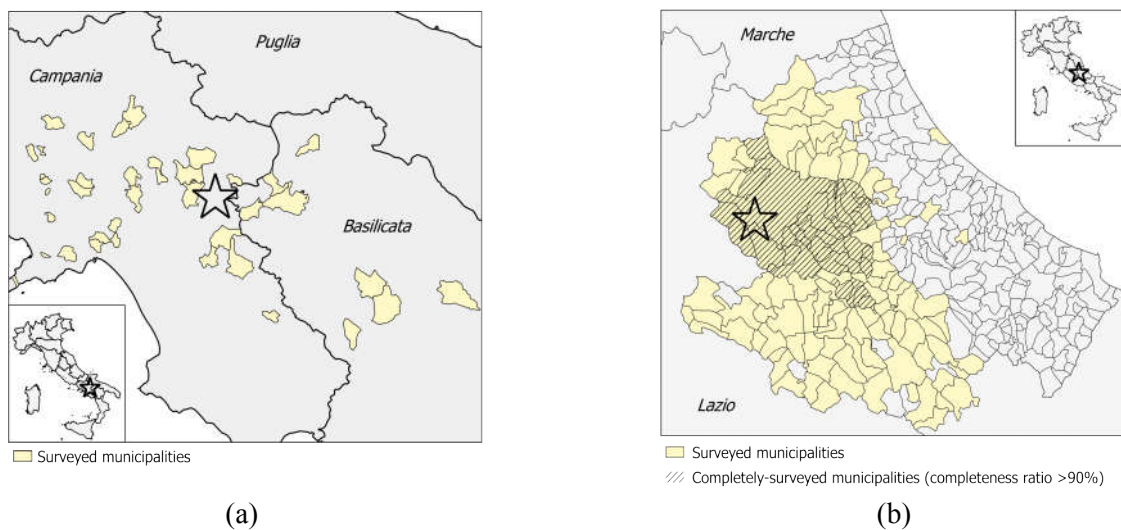


Fig. 1 – Identification of the municipalities surveyed after the 1980 Irpinia (a) and the 2009 L'Aquila (b) earthquakes. Adapted from Rosti et al. [10].

2.1 Characterization of the ground motion severity

Seismic input was defined at the building locations by assigning a seismic intensity measure representative of the ground shaking. Although various ground motion intensity measures can be adopted for seismic input description (e.g. [17]), the peak ground acceleration (PGA) was selected, allowing for complying with the key characteristics of the Italian national seismic risk platform [12]. Values of PGA were evaluated at the damage locations via shakemaps (Fig. 2), consistently derived with the Italian National Institute of Geophysics and Volcanology (INGV) procedure [18], which takes advantage of different ground motion prediction equations (GMPEs) and of signals registered by the Italian Strong Motion Network (RAN) and by the Italian National Seismic Network (RSN).

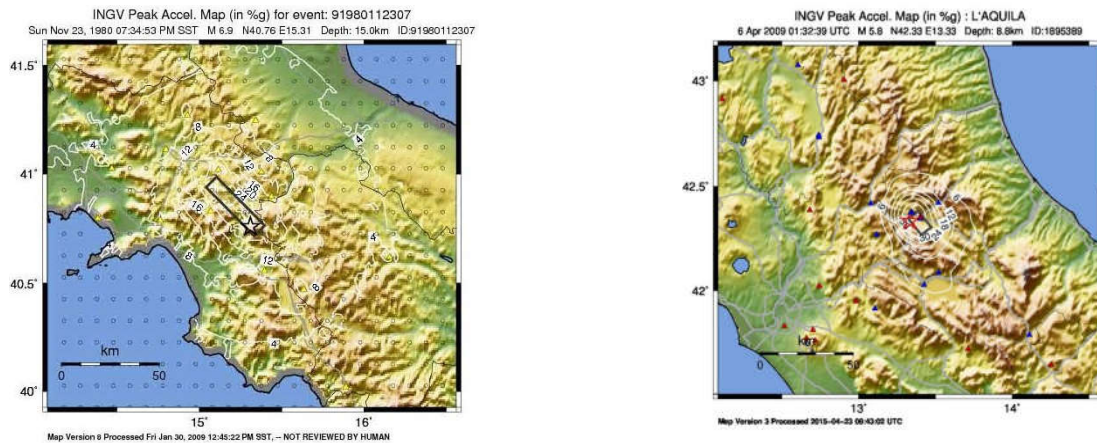


Fig. 2 – Shakemaps of the 1980 Irpinia [18] and of the 2009 L'Aquila (<http://shakemap.rm.ingv.it/shake/index.html>) seismic events

2.2 Typological classification of RC buildings

Considering the information available from the post-earthquake damage databases, RC buildings were subdivided based on the number of stories and construction age (Fig. 3). The majority of the Irpinia RC buildings, for which the construction age is known, was built after 1962. Differently, about 34% of the L'Aquila RC buildings was built before 1981 and 66% following 1981. Considering the number of stories, 66% of the Irpinia RC buildings is low-rise (i.e. characterized by 1 or 2 stories), 30% is mid-rise (i.e. 3 or 4 stories) and 4% has more than 4 stories. A different trend is instead observed in case of the L'Aquila RC buildings, 29% of which has 1 or 2 stories, 64% is mid-rise (i.e. 3 or 4 stories) whereas 7% has more than 4 stories.

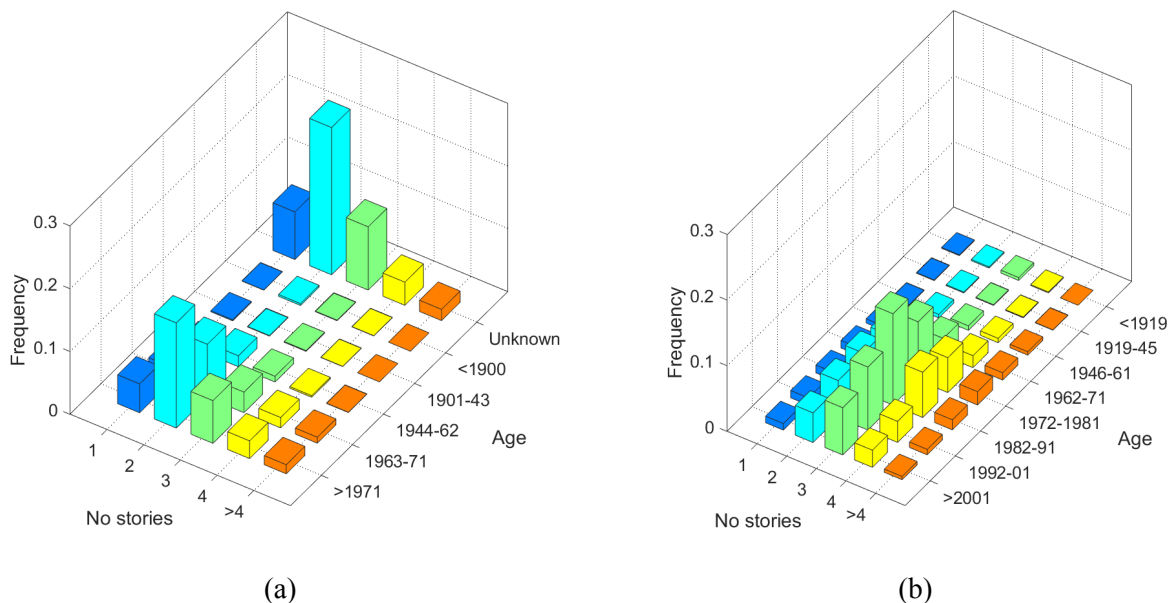


Fig. 3 – Subdivision of the Irpinia (a) and L'Aquila (b) building stock based on the number of stories and construction age. Adapted from Rosti et al. [19].

RC buildings were then classified into fifteen building typologies, identified based on the number of stories (from 1 to 5) and design level, to account for building code evolution. For each building, the level of design was determined by comparing the age of construction with the year of first seismic classification of



the municipality where the building was located. Three levels of design were considered: RC buildings designed for gravity loads only, RC buildings with seismic design pre-1981 and RC buildings seismically designed after 1981. Gravitational RC buildings derive from the Irpinia database, since most of the Irpinia municipalities were not classified as “seismic” in 1980, whilst most of the L’Aquila municipalities were classified as “seismic” since 1915 [20]. Distinction between pre- and post-1981 seismically designed RC buildings was considered to account for the evolution of technical codes [21] and for consistency between the considered post-earthquake databases. Fig. 4 shows the typological classification of RC buildings, based on post-earthquake data.

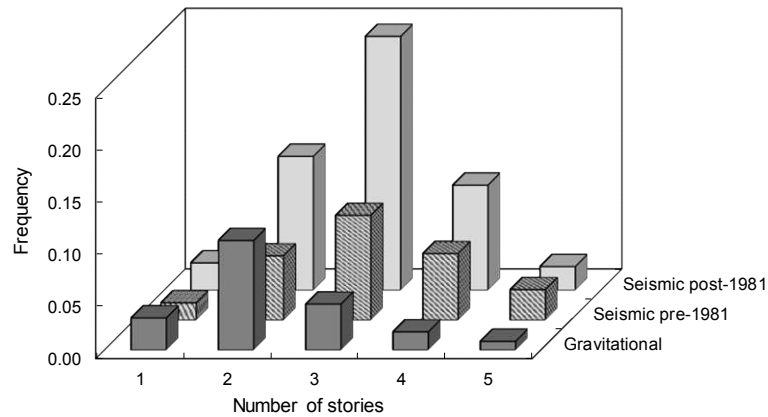


Fig. 4 – Typological classification of RC buildings based on post-earthquake damage data

2.3 Damage classification

A global level of damage, consistent with the EMS-98 scale [22], was assigned to each inspected building. To convert the damage description available from the survey forms into discrete damage levels, suitable damage conversion rules were adopted. In particular, the damage rule proposed by Braga et al. [1] and Dolce et al [13] was employed in case of the Irpinia damage dataset, whereas, in case of the L’Aquila dataset, the Rota et al. [5] and the Del Gaudio et al. [7] rules were adopted for structural and non-structural damage, respectively (Table 1).

Table 1 – Damage conversion rules adopted for damage classification of RC buildings

Damage level	Irpinia survey form		L’Aquila survey form	
	Structural components [1], [13]	Non-structural components	Structural components [5]	Non-structural components [7]
DS0	No damage	No damage	D0	D0
DS1	Insignificant Slight	Insignificant Slight	D1 - <1/3 D1 - 1/3-2/3 D1 - > 2/3	D1 - <1/3 D1 - 1/3-2/3 D1 - > 2/3
DS2	Considerable Serious	Considerable Serious	D2 - D3 - <1/3	D2 - D3 - <1/3 D2 - D3 - 1/3-2/3 D2 - D3 - > 2/3
DS3	Very-serious	Very-serious Partially-collapsed Collapsed	D2 - D3 - 1/3 – 2/3 D2 - D3 - > 2/3	D4 - D5 - <1/3 D4 - D5 - 1/3-2/3 D4 - D5 - > 2/3
DS4	Partially-collapsed		D4 - D5 - <1/3 D4 - D5 - 1/3-2/3	
DS5	Collapsed		D4 - D5 - >2/3	



The adoption of different damage conversion rules was due to the fact that, in the aftermath of the two seismic events, buildings' inspections were carried out by using different post-earthquake survey forms. Damage levels were first evaluated on individual building components, that is vertical structure and masonry infills/partitions. In line with existing studies (e.g. [3], [7]), a global level of damage was then attributed to each building, by considering the maximum damage level observed between the vertical structure and masonry infills/partitions. Fig. 5 (a) shows the geographical distribution of damage, with reference to the L'Aquila completely surveyed municipalities, whilst Fig. 5 (b) depicts the overall damage distributions resulting from each seismic event.

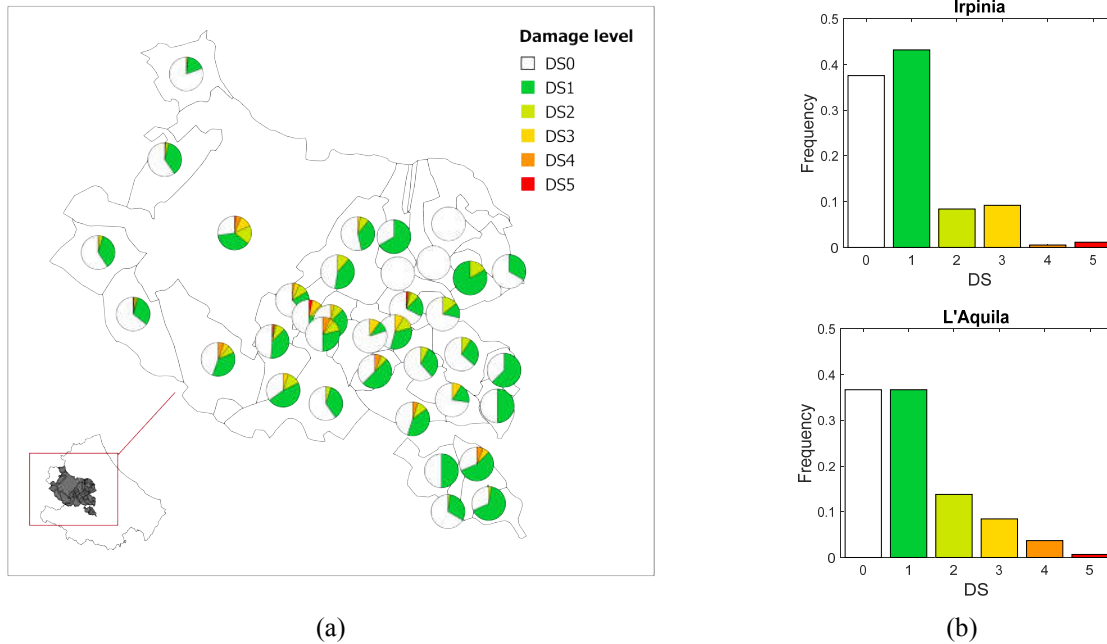


Fig. 5 – Damage distributions in the L'Aquila completely-surveyed municipalities. Adapted from Rosti et al. [19] (a) and overall damage distributions of the Irpinia and L'Aquila events (b).

2.4 Adopted statistical model and fitting procedure

The derivation of fragility curves requires the selection of a suitable statistical model to be fitted to observational data points. In this work, the probability of reaching or exceeding a given damage level, as a function of the peak ground acceleration, was described by the cumulative lognormal distribution, similarly to existing studies (e.g. [5], [7]):

$$P(ds \geq DS_i | PGA_j) = \Phi \left[\frac{\ln(PGA_j / \theta_{DS_i})}{\beta} \right] \quad (1)$$

where $\Phi[\cdot]$ is the cumulative standard normal distribution, θ_{DS_i} is the median PGA value associated with damage level DS_i and β is the logarithmic standard deviation. For all levels of damage, a unique constant value of dispersion (β) was assumed to ensure non-crossing fragility curves (e.g. [10]).

The multinomial distribution (e.g. [23]) was adopted for approximating the repartition of buildings in the different damage states (from DS0 to DS5), n_{ij} , for a given PGA threshold, PGA_j :

$$n_{ij} \sim \prod_{i=0}^5 \frac{N_j!}{n_{ij}!} P(ds = DS_i | PGA_j)^{n_{ij}} \quad (2)$$

where N_j indicates the total number of buildings corresponding to the PGA threshold PGA_j and $P(ds=DS_i|PGA_j)$ is the probability of occurrence of damage state DS_i given PGA_j .



The parameters of the fragility model (i.e. θ and β) were estimated by simultaneously fitting the fragility functions to empirical data points, through the by maximum likelihood approach:

$$(\theta, \beta) = \arg \max[\log(L(\theta, \beta))] = \arg \max \left[\log \left(\prod_{j=1}^{n_{PGA}} \prod_{i=0}^{n_{DS}} \frac{N_j!}{n_{ij}!} P(ds = DS_i | PGA_j)^{n_{ij}} \right) \right] \quad (3)$$

3. Derivation of empirical fragility curves

Empirical fragility curves were derived for fifteen building typologies, identified based on the number of stories and design level (Fig. 4). As an example, Fig. 6 shows empirically-derived fragility curves of two-story and four-story RC buildings, with different design levels, i.e. buildings designed for gravity loads only and for seismic loads pre- and post-1981. It can be observed that seismic vulnerability reduces with the improvement of the design level.

Starting from the typological classification of the existing building stock, two vulnerability classes (i.e. C2 and D), of decreasing vulnerability, were defined to make the proposed fragility model easily usable for territorial seismic vulnerability and risk applications, based on census data. In particular, vulnerability class C2 gathers together gravitational RC buildings and pre-1981 RC buildings with seismic design. Vulnerability class D instead includes RC buildings seismically designed after 1981. Vulnerability classes were then refined based on the building height, i.e. low-rise (L: 1-2 stories), mid-rise (M: 3-4 stories) and high-rise (H: > 4 stories). Empirical fragility curves were hence derived for vulnerability classes and classes of building height, as weighted average of the typological fragility curves (Fig. 7). To this aim, weights were defined by the frequency of occurrence of predefined building typologies, which was evaluated at the national scale based on census data.

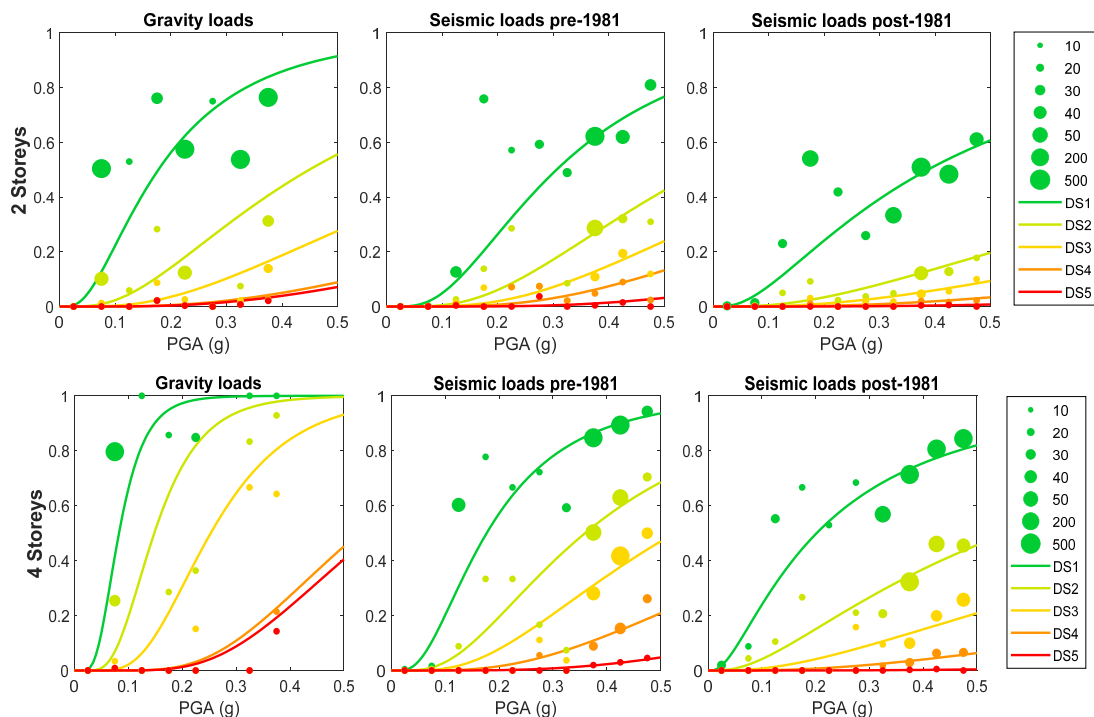


Fig. 6 – Empirical fragility curves for two-story RC buildings with different design levels (i.e. gravity loads, seismic loads pre-1981, seismic loads post-1981).

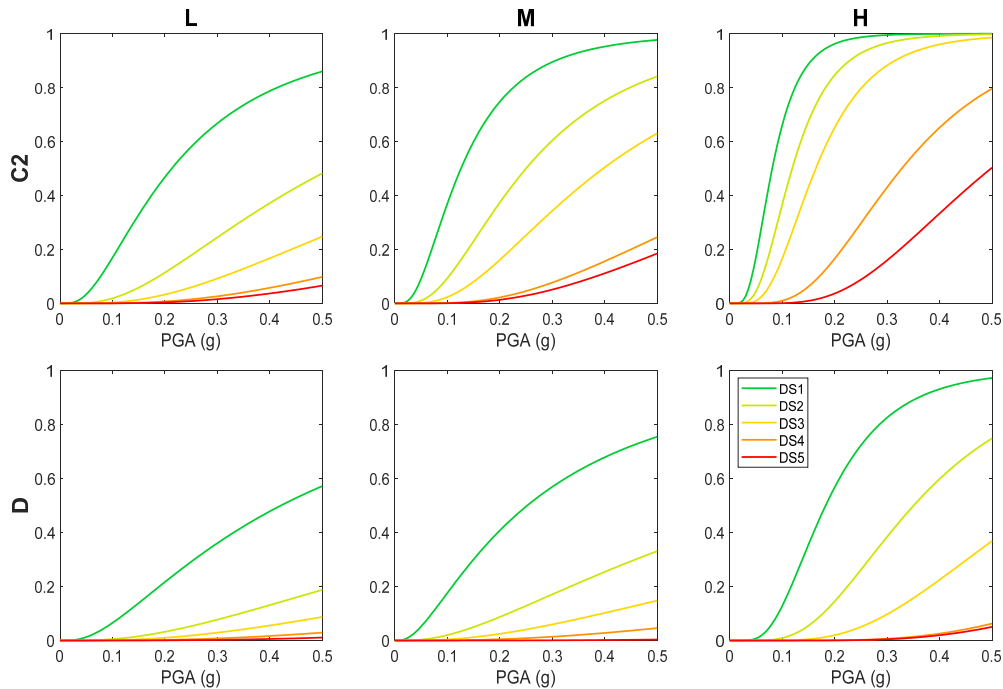


Fig. 7 – Empirically-derived fragility curves for vulnerability classes C2 and D and classes of building height (i.e. L: low-rise, M: mid-rise and H: high-rise). Adapted from Del Gaudio et al. [11].

4. Territorial seismic risk assessment: case-study application

To demonstrate the suitability of the presented empirically-derived fragility model for large-scale seismic risk evaluations, a case-study application is presented, with reference to the Campania region (Fig. 8). The example of application was carried out by implementing the empirical fragility model (Fig. 7) in the Italian national seismic risk platform [12], where seismic hazard is defined by the MPS04 seismic hazard model [24][25], whereas exposure derives from national census data [15]. Fig. 8 (a) shows the exposed number of RC buildings in each municipality of the Campania region [15], whereas Fig. 8 (b) shows the geographical distribution of the percentages of RC buildings belonging to the vulnerability classes C2 and D.

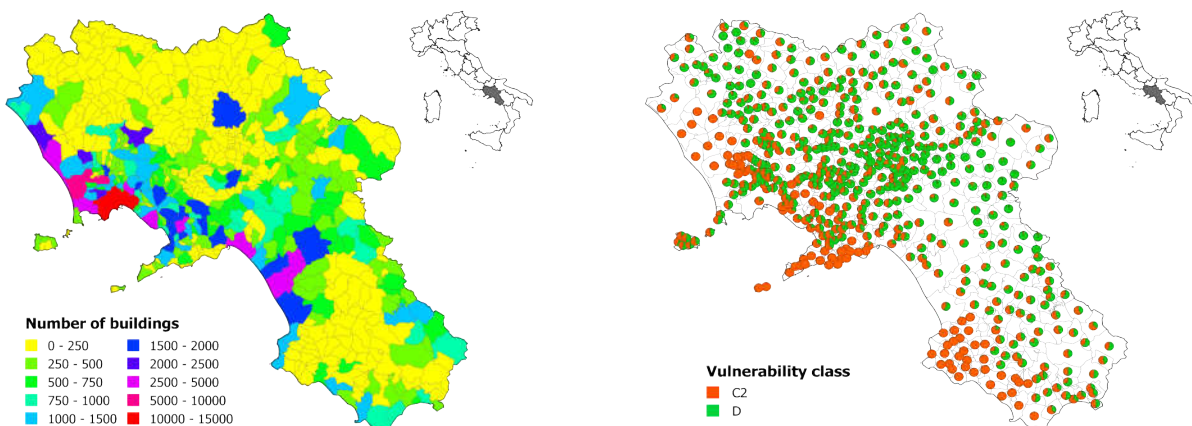


Fig. 8 – Exposed number of RC buildings per municipality of the Campania region [15] (a) and percentages of RC buildings belonging to vulnerability classes C2 and D (b).

Of the 241'277 RC buildings of the Campania region, 56% belongs to vulnerability class C2 and 44% to vulnerability class D. The considerable percentages of RC buildings belonging to vulnerability class D,



observed in several municipalities, is explained by the reconstruction process following the Irpinia earthquake, which led to a prevalence of post-1981 RC buildings seismically designed.

Seismic risk was quantified in terms of physical damage annually expected on the RC building stock. Results are reported in Fig. 9, in the form of regional seismic risk maps, showing the geographical distribution of the percentages of RC buildings exceeding preselected damage levels (from DS1 to DS5), in one year. A similar application with reference to masonry buildings is presented in [26].

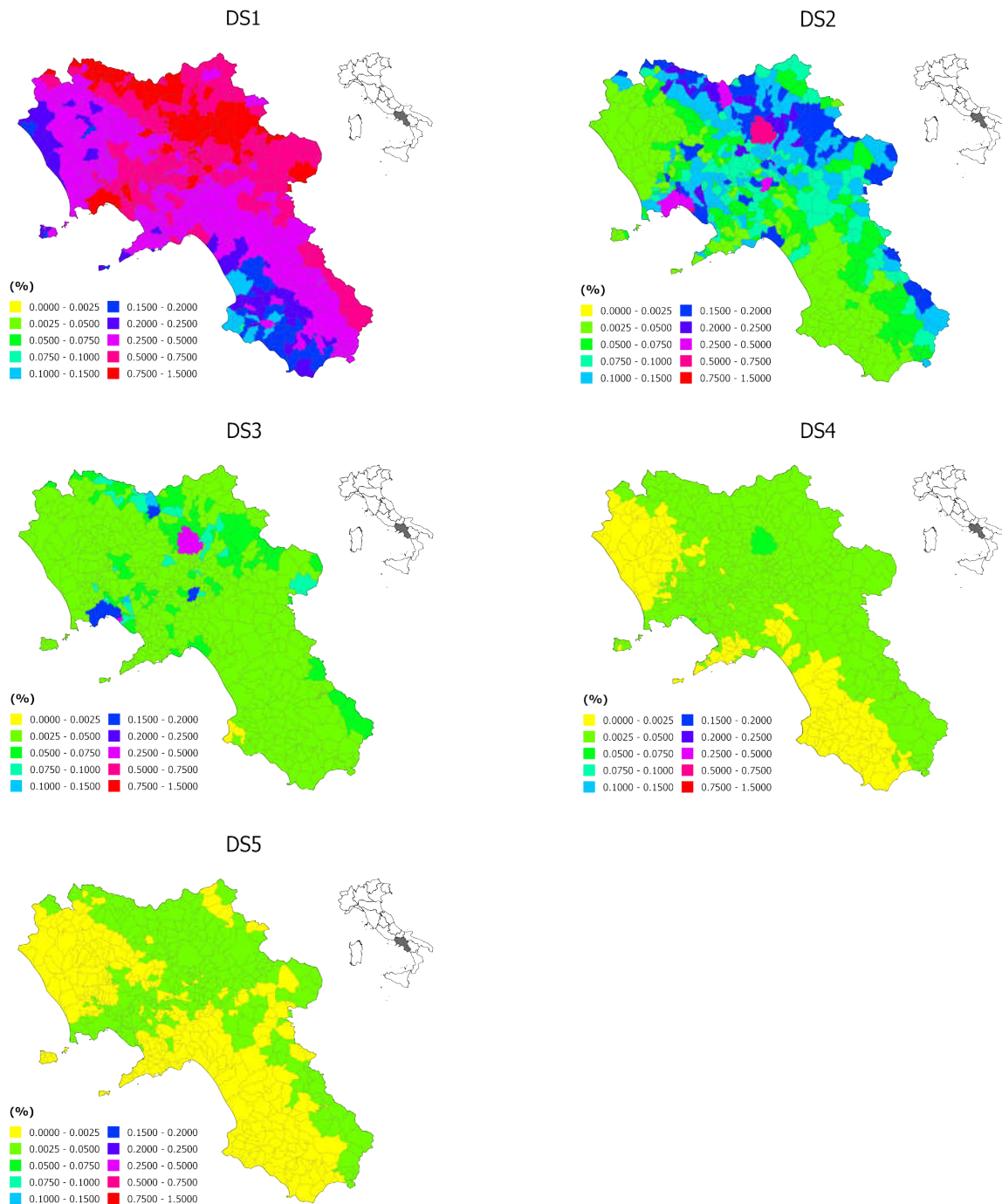


Fig. 9 – Maps of the expected percentages of RC buildings exceeding different damage states (from D1 to DS5), in one year.



5. Conclusions

Empirical fragility curves for residential RC buildings are derived by statistically elaborating post-earthquake damage data related to Italian seismic events of the period 1980-2009. The peak ground acceleration, estimated from shakemap, is employed for representing the ground motion severity experienced at the different building locations. Fifteen building typologies are identified based on the number of stories (from 1 to 5) and type of design (i.e. gravity loads, seismic loads pre-1981 and seismic loads post-1981) and suitable damage rules are adopted for converting the damage description of the post-earthquake survey form into discrete global levels of damage consistent with the EMS-98. Empirical fragility curves are derived for predefined building typologies, by fitting a cumulative lognormal distribution to observational data points and by assuming the multinomial model to describe the subdivision of buildings in the different damage states, given the peak ground acceleration. Starting from the typological classification of the building stock, two vulnerability classes of decreasing vulnerability are then defined. Empirical fragility curves are hence derived for vulnerability classes and classes of building height, by suitably averaging typological fragility curves, based on their frequency of occurrence evaluated at the national scale. A case-study application, carried out through the Italian national seismic risk platform, is also illustrated to show the feasibility of the presented empirical fragility model to be used for territorial seismic risk evaluations.

6. Acknowledgements

This work was carried out under the financial support of the Italian Department of Civil Protection within the ReLUIIS-DPC 2018 project. This support is gratefully acknowledged.

7. References

- [1] Braga F, Dolce M, Liberatore D (1982): A statistical study on damaged buildings and an ensuing review of the M.S.K.-76 scale. *7th European Conference on Earthquake Engineering*, Athens, Greece.
- [2] Di Pasquale G, Orsini G, Romeo RW (2005): New developments in seismic risk assessment in Italy. *Bulletin of Earthquake Engineering*, **3**(1), 101-128.
- [3] Rosti A, Rota M, Penna A (2018): Damage classification and derivation of damage probability matrices from L'Aquila (2009) post-earthquake survey data. *Bulletin of Earthquake Engineering*, **16**, 3687-3720.
- [4] Rossetto T, Elnashai A (2003): Derivation of vulnerability functions for European-type RC structures based on observational data. *Engineering Structures*, **25**(10), 1241-1263.
- [5] Rota M, Penna A, Strobbia CL (2008): Processing Italian damage data to derive typological fragility curves. *Soil Dynamics & Earthquake Engineering*, **28**, 933-947.
- [6] Rossetto T, Ioannou I, Grant DN (2013): *Existing empirical vulnerability and fragility functions: compendium and guide for selection*. GEM Technical Report 2013-X, GEM Foundation, Pavia, Italy.
- [7] Del Gaudio C, De Martino G, Di Ludovico M, Manfredi G, Prota A, Ricci P, Verderame GM (2017): Empirical fragility curves from damage data on RC buildings after the 2009 L'Aquila earthquake. *Bulletin of Earthquake Engineering*, **15**, 1425-1450.
- [8] 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. *Bulletin of Earthquake Engineering*, **14**, 2643-2678.
- [9] Rota M, Penna A, Strobbia C, Magenes G (2011): Typological seismic risk maps for Italy. *Earthquake Spectra*, **27**, 907-926.
- [10] Rosti A, Rota M, Magenes G, Penna A (2019): A procedure for seismic risk assessment of Italian masonry buildings. *7th ECCOMAS Thematic Conference on Computational Methods in Structural Dynamics and Earthquake Engineering*, Crete, Greece.



- [11] Del Gaudio C, Di Ludovico M, Magenes G, Penna A, Polese M, Prota A, Ricci P, Rosti A, Rota M, Verderame GM (2019): A procedure for seismic risk assessment of Italian RC buildings. *7th ECCOMAS Thematic Conference on Computational Methods in Structural Dynamics and Earthquake Engineering*, Crete, Greece.
- [12] Borzi B, Faravelli M, Onida M, Polli D, Quaroni D, Pagano M, Di Meo A (2018): IRMA Platform (Italian Risk Maps). *37^o National Conference GNGTS*, Bologna, Italy.
- [13] Dolce M, Speranza E, Giordano F, Borzi B, Bocchi F, Conte C, Di Meo A, Faravelli M, Pascale V (2019): Observed damage database of past Italian earthquakes: the Da.D.O. Webgis. *Bollettino di Geofisica Teorica e Applicata*, **60** (2), 141-164.
- [14] Dolce M, Goretti A (2015): Building damage assessment after the 2009 Abruzzi earthquake. *Bulletin of Earthquake Engineering*, **13** (8), 2241-2264.
- [15] Census Data (2001): <http://dawinci.istat.it/jsp/MD/dawinciMD.jsp>.
- [16] Karababa FS, Pomonis A (2011): Damage data analysis and vulnerability estimation following the August 14, 2003 Lefkada Islanda, Greece, Earthquake. *Bulletin of Earthquake Engineering*, **9**, 1015-1046.
- [17] Rosti A, Rota M, Penna A (2020): Influence of seismic input characterization on empirical damage probability matrices for the 2009 L'Aquila event. *Soil Dynamics & Earthquake Engineering*, **128**, 105870, doi.org/10.1016/j.soildyn.2019.105870.
- [18] Michelini A, Faenza L, Lauciani V, Malagnini L (2008): Shakemap implementation in Italy. *Seismological Research Letters*, **79**, 688-697.
- [19] Rosti A, Del Gaudio C, Di Ludovico M, Magenes G, Penna A, Polese M, Prota A, Ricci P, Rota M, Verderame GM (2020): Empirical vulnerability curves for Italian residential buildings. *Bollettino di Geofisica Teorica e Applicata*, **61**, Accepted.
- [20] R.D.L. 29/04/1915, n. 573 Regio Decreto Legge "Norme tecniche ed igieniche da osservarsi per i lavori edilizi nelle località colpite dal terremoto del 13/01/1915". *Gazzetta ufficiale* 11/05/1915 n. 117.
- [21] D.M. 03/03/1975, Decreto Ministeriale "Approvazione delle norme tecniche per le costruzioni in zone sismiche". *Gazzetta ufficiale* 08/04/1975 n. 93.
- [22] Grünthal G. (ed.), Musson RMW, Schwarz J, Stucchi M (1998): European Macroseismic Scale. *Cahiers du Centre Européen de Géodynamique et de Séismologie*, Vol. 15 - European Macroseismic Scale 1998. European Centre for Geodynamics and Seismology, Luxembourg, 1998.
- [23] Charvet I, Ioannou I, Rossetto T, Suppasri A, Imamura F (2014): Empirical fragility assessment of buildings affected by the 2011 Great East Japan tsunami using improved statistical models. *Natural Hazards*, **73**, 951-973.
- [24] Stucchi M, Akinci A, Faccioli E, Gasperini P, Malagnini L, Meletti C, Montaldo V, Valensise G (2004): Mappa di pericolosità sismica del territorio nazionale. <http://zonesismiche.mi.ingv.it/documenti/rapportoconclusivo.pdf>.
- [25] Stucchi M, Meletti C, Montaldo V, Crowley H, Calvi GM, Boschi E (2011): Seismic hazard assessment (2003-2009) for the Italian building code. *Bulletin of the Seismological Society of America*, **101**(4), 1885-1911.
- [26] Rosti A, Rota M, Penna A (2020): Derivation of fragility curves for Italian masonry buildings from post-earthquake damage data. *17th World Conference on Earthquake Engineering, 17WCEE*, Sendai, Japan.