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

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## *Abstract*

Empirical fragility curves for residential masonry buildings are derived by statistically processing post-earthquake damage data from past Italian events. Data interpretation and homogenization is first carried out to consistently classify masonry buildings into predefined building typologies and levels of damage. Eight building typologies are identified based on the quality and layout of the masonry fabric, in-plane stiffness of intermediate diaphragms, presence (or absence) of connecting devices (e.g. tie-rods, tie-beams). Suitable damage conversion rules are employed to convert the damage description of the survey forms into the EMS-98 discrete damage levels, whereas the peak ground acceleration, estimated from shakemap, is adopted for seismic input characterization at building locations. Typological fragility curves are first derived by fitting a cumulative lognormal distribution to observational damage data, through the maximum likelihood estimate approach. The multinomial distribution is adopted to describe the repartition of buildings in the different damage states, given the intensity measure. To make the proposed fragility model easily usable for territorial risk applications, fragility curves are then derived for three vulnerability classes of decreasing vulnerability (i.e. high, medium and low), identified based on the similarity of the observed seismic vulnerability of the building typologies. To this aim, an agglomerative clustering strategy is built up, to iteratively merge predefined building typologies into wider clusters, up to the definition of three vulnerability classes, then refined based on the building height. A case-study application is also presented, to demonstrate the feasibility of the proposed empirically-derived fragility model for territorial seismic risk evaluations.

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

## 1. Introduction

The evaluation of seismic vulnerability, representing the propensity of a building to be damaged by a seismic event, is a key ingredient not only for the quantification of seismic risk, but also for the definition of mitigation and retrofit programs and for the development or improvement of building codes.

Approaches for seismic vulnerability assessment are typically classified into empirical, analytical, expert-judgmental and hybrid. The choice of using one rather than another method depends on both the source of available data and the aim of the study. In this context, empirical approaches exploit post-earthquake damage data to derive either Damage Probability Matrices (DPMs), representing the damage distribution of a given building typology, conditioned on the selected intensity measure (e.g. [1], [2]), or fragility curves, providing continuous relations between the observed seismic damage and the selected ground motion intensity measure (e.g. [3], [4], [5], [6], [7]). Thanks to their statistical nature, observational approaches are more appropriate for large scale applications rather than for the assessment of single buildings (e.g. [8], [9], [10], [11]).

The credibility of empirical data may be questioned by different sources of uncertainty, which require to be carefully addressed for a reliable quantification of the seismic vulnerability (e.g. [6]). Nevertheless, if accurately processed, post-earthquake damage data represent a unique and invaluable source of information on the seismic vulnerability of the existing building stock.

This study derives empirical fragility curves for Italian residential masonry buildings, to be used for territorial seismic vulnerability and risk applications. The proposed fragility model is derived by statistical processing empirical damage data collected after the main Italian earthquakes occurred in the period 1980-2009 and it is also compatible with the key characteristics of the Italian national seismic risk platform ([12], http://irma.eucentre.it/irma/web/home). A process of data interpretation and homogenization, to uniformly allocate damage data to predefined building typologies and levels of damage, is first presented (Section 2). Empirical fragility curves are then derived for eight masonry building typologies, representative of the Italian building stock, then associated to three vulnerability classes of decreasing vulnerability (Section 3). The feasibility of the proposed empirically-derived fragility model for territorial seismic risk evaluations is demonstrated through an example of application (Section 4).

## 2. The post-earthquake damage database

This study proposes an empirically-derived fragility model, obtained by statistically processing empirical damage data available in the Da.D.O. platform [13], collecting post-earthquake damage data of the main Italian seismic events occurred from 1980 to 2012. Two seismic events are considered in this study, namely the Irpinia (1980) and the L'Aquila (2009) earthquakes (Fig. 1). The use of the damage databases of these two seismic events is motivated by the availability of shakemaps, consistently defined and adopted for seismic input characterization, by the considerable amount of damage data, and by the availability of complete post-earthquake damage data.

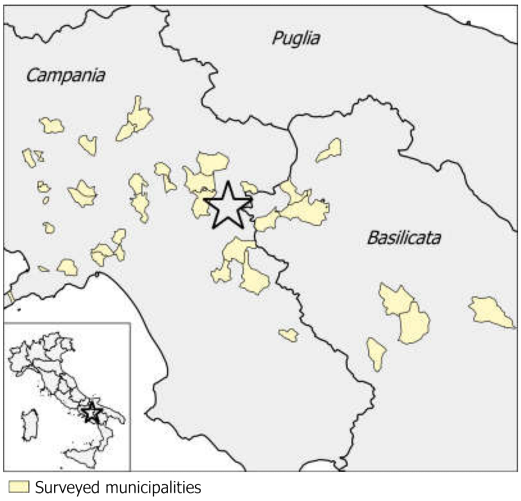
As pointed out by Rossetto et al. [6], under-coverage errors in post-earthquake damage databases represent one of the major sources of bias in empirical data. This issue arises when post-earthquake field surveys are carried out on request of the building owner only, with the consequence that the survey is not complete and tends to be limited to buildings with some level of damage, leading to post-earthquake damage databases mostly including damaged buildings only. Therefore, if the number of undamaged buildings is not suitably accounted for, resulting damage distributions may be biased by the fact that the number of undamaged buildings is underestimated. This issue is more critical in the areas less affected by the earthquake, where it is very likely that non-inspected buildings were not surveyed because undamaged.

As indicated in [1], all the municipalities of the Irpinia database were completely surveyed. Differently, after the L'Aquila earthquake, the survey of residential buildings was 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 case of the L'Aquila event, the municipalities with completeness ratio (i.e.

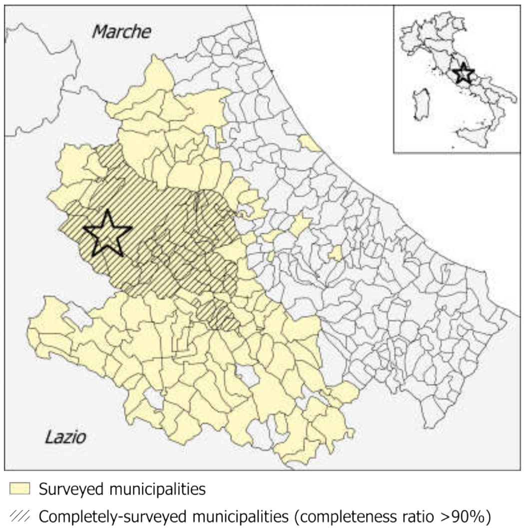


number of inspected buildings over the total number of buildings evaluated from national census [15]) exceeding 90% (selected completeness threshold) were considered to be completely surveyed. The resulting post-earthquake damage dataset counted about 50’000 masonry buildings. To account for the negative evidence of damage in the territories less affected by the ground shaking (e.g. [5]), the post-earthquake damage dataset was then enlarged by adding 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 and 49 municipalities were instead characterized by a completeness ratio lower than 10%. The number of masonry buildings located in these municipalities was retrieved from national building census [15] and added to the database as undamaged buildings.




(a)




(b)

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 Seismic input characterization

Seismic input characterization aims at assigning a value of the selected seismic intensity measure, representative of the ground shaking at the damage locations. Although alternative seismic intensity measures could be adopted for seismic input definition [16], the peak ground acceleration (PGA) was selected in this study, to make the proposed fragility model compatible with the key characteristics of the Italian national seismic risk platform [12].

Values of PGA were estimated at the building locations by shakemaps (Fig. 2), consistently defined with the INGV procedure [17]. In case of the Irpinia damage data, isoseismic units were defined at the municipality level, whereas, in case of the L’Aquila damage data, seismic input was characterized at the building level, given the availability of accurately georeferenced data.



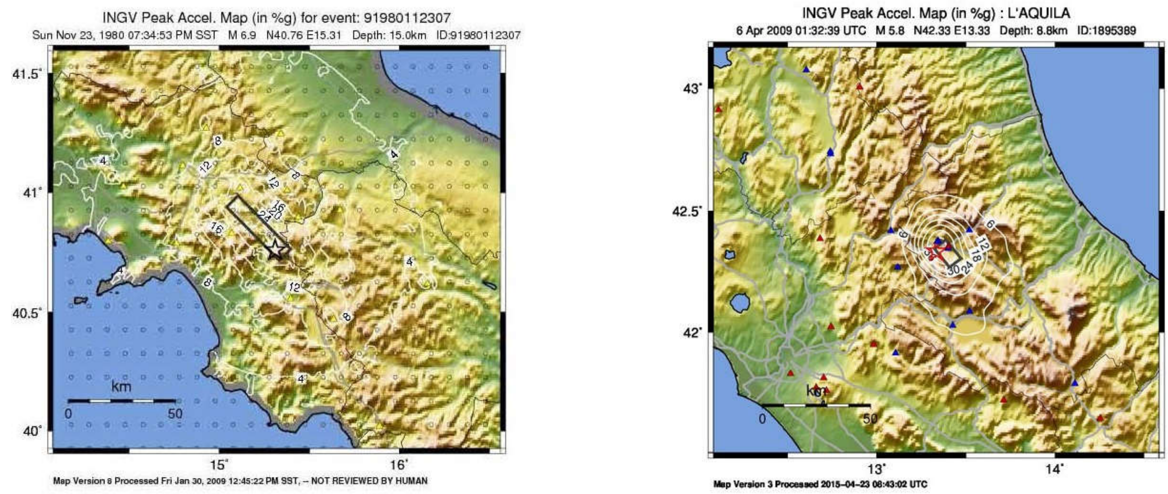



Fig. 2 – Shakemaps of the 1980 Irpinia [17] and of the 2009 L'Aquila (http://shakemap.rm.ingv.it/shake/index.html.) seismic events

## 2.3 Building taxonomy

Masonry buildings were classified into eight building typologies representative of the Italian building stock (Table 1), based on the typological classification system proposed by Rota et al. [4]. Taking advantage of typological building attributes available from post-earthquake survey forms, masonry buildings were hence classified considering:

- Layout and quality of the masonry fabric (i.e. IRR: irregular layout or poor-quality masonry and REG: regular layout and good-quality masonry)
- In-plane stiffness of intermediate diaphragms (i.e. F: flexible and R: rigid)
- Presence (or absence) of connecting devices, such as tie-rods and/or tie-beams (i.e. NCD: without connecting devices and CD: with connecting devices).

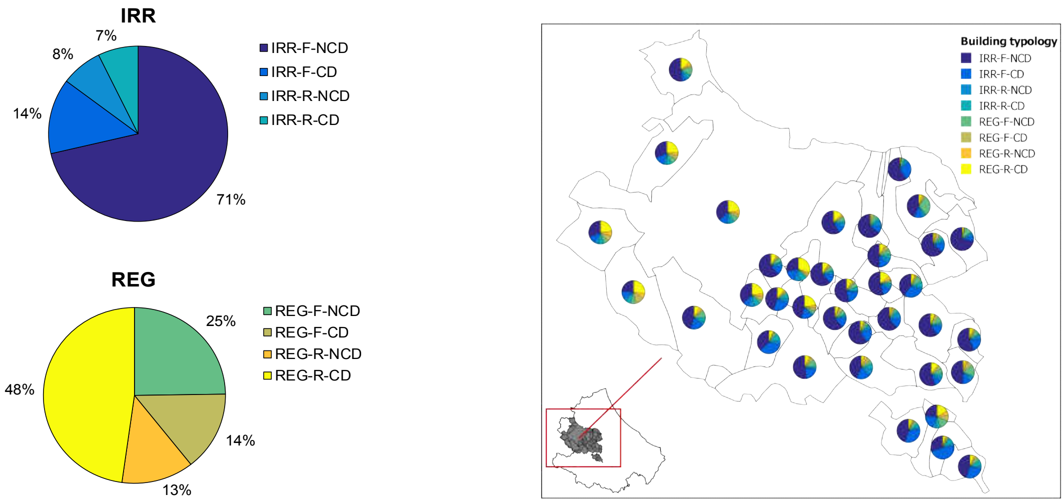
Table 1 – Adopted building taxonomy [4]

| **Masonry type** | **Diaphragm** | **Presence of connecting devices?** | **Label** |
|---|---|---|---|
| Irregular layout or poor-quality (IRR) | Flexible (F) | No (NCD) | IRR-F-NCD |
| | | Yes (CD) | IRR-F-CD |
| | Rigid (R) | No (NCD) | IRR-R-NCD |
| | | Yes (CD) | IRR-R-CD |
| Regular layout and good-quality (REG) | Flexible (F) | No (NCD) | REG-F-NCD |
| | | Yes (CD) | REG -F-CD |
| | Rigid (R) | No (NCD) | REG -R-NCD |
| | | Yes (CD) | REG -R-CD |



Fig. 3 (a) shows the typological classification of the considered dataset. About 77% of masonry buildings are made of poor-quality materials or characterized by irregular texture of the masonry fabric, whereas 23% exhibit regular layout and good-quality masonry. About 71% of irregular layout or poor-quality masonry buildings have flexible diaphragms and lack connecting devices. Differently, about 48% of buildings with regular layout and good-quality masonry exhibit rigid intermediate diaphragms and tie-rods and/or tie-beams. Fig. 3 (b) shows the distribution of predefined building typologies with reference to the L'Aquila completely-surveyed municipalities.




(a) (b)

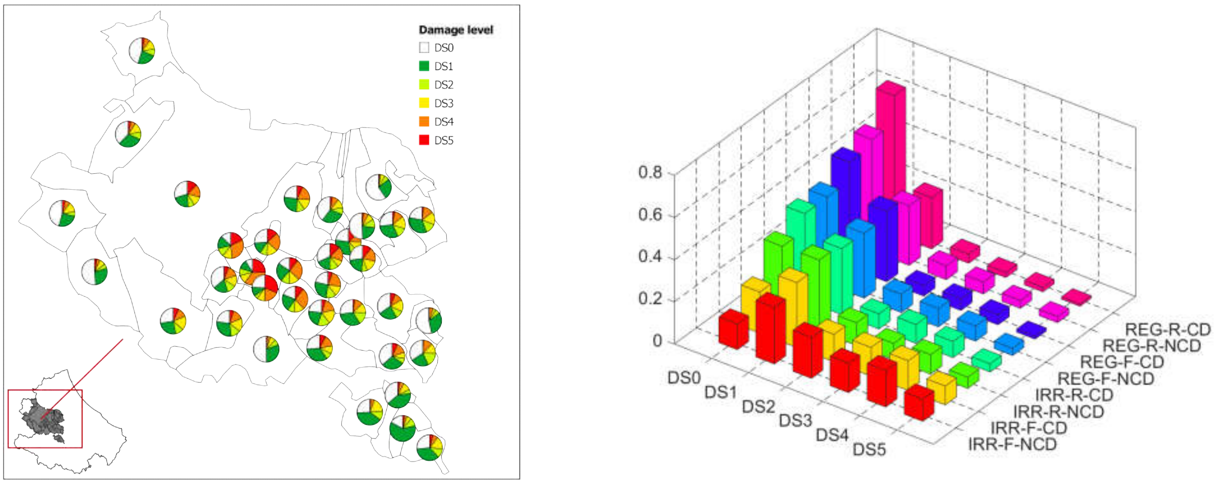
Fig. 3 – Typological classification of masonry buildings (a) and distribution of building typologies in the L'Aquila completely-surveyed municipalities (b)

## 2.2 Damage classification

Damage levels were defined consistently with the EMS-98 scale [18], by adopting damage rules from literature for converting the damage description of the survey forms into discrete levels of damage. The conversion rule proposed by Braga et al. [1] and Dolce et al [13] was employed in case of the Irpinia data, whilst the Rota et al. [4] damage rule was used for the L'Aquila damage data. The need of using different damage conversion rules derives from the fact that different survey forms were used for building inspections after the considered seismic events. After evaluating damage individually on preselected building components, that is vertical structure, intermediate diaphragms and roof, a global damage level was assigned to each building by considering the maximum observed seismic damage (e.g. [2], [4]). Fig. 4 (a) shows the spatial distribution of damage, with reference to the L'Aquila completely-surveyed municipalities. Fig. 4 (b) depicts the damage distribution conditioned on building typologies and considering damage data from both seismic events.






(a) (b)

Fig. 4 – Damage distributions in the L'Aquila completely-surveyed municipalities (a) and damage distributions conditioned on building typologies (b). Adapted from Rosti et al. [10],[19].

## 3. Derivation of empirical fragility curves

The derivation of fragility curves requires a statistical model to be fitted to empirical data points through a suitable fitting procedure. In accordance with existing studies (e.g. [4],[7]), the probability of reaching or exceeding a given damage level, as a function of the selected intensity measure, was described by the cumulative lognormal distribution:

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

where $\Phi[\cdot]$ is the cumulative standard normal distribution, $\theta_{DSi}$ is the median PGA value associated with damage level $DS_i$ and $\beta$ is the logarithmic standard deviation. A unique constant value of dispersion ($\beta$) was considered for all levels of damage. Although reducing the model flexibility, this assumption allows to avoid intersecting fragility functions.

For a given PGA threshold, $PGA_j$, the subdivision of buildings in the different damage states (from DS0 to DS5), $n_{ij}$, was approximated by the multinomial distribution [20]:

$$n_{ij} \sim \prod_{i=0}^{n} \frac{N_j!}{n_{ij}!} P\left(ds = DS_i \middle| PGA_j\right)^{n_{ij}} \tag{2}$$

where $N_j$ is 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 unknown parameters of the fragility model (i.e. $\boldsymbol{\theta}$ and $\beta$) were obtained by simultaneously fitting the fragility functions to empirical data points by maximizing the logarithm of the likelihood:

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

Fig. 5 shows empirical fragility curves derived for the eight building typologies listed in Table 1. As expected, the layout and quality of the masonry fabric affects buildings' seismic vulnerability. Building typologies with irregular layout or poor-quality masonry are indeed significantly more vulnerable than the corresponding ones with regular layout and good-quality materials. Observation of Fig. 5 shows that building typologies with flexible diaphragms are more vulnerable than the corresponding ones with rigid diaphragms and that the presence of aseismic devices, such as tie-rods and/or tie-beams, reduces buildings' seismic vulnerability.

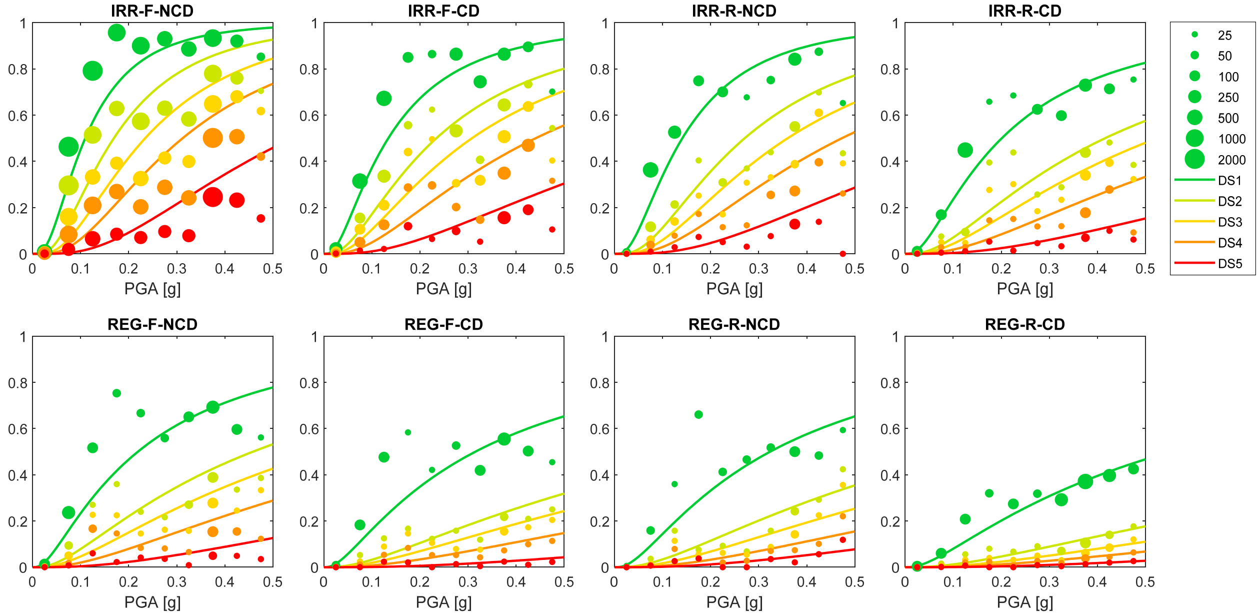



Fig. 5 – Empirical fragility curves for Italian masonry building typologies. Adapted from Rosti et al. [10]

Starting from the typological classification of the existing building stock, three vulnerability classes of decreasing vulnerability (i.e. A: high vulnerability, B: medium vulnerability and C1: low vulnerability) were then defined. Existing studies (e.g. [14], [21]) generally associate building typologies to vulnerability classes based on the rule proposed by Braga et al. [1], resulting from the best agreement between the Irpinia (1980) post-earthquake damage data and the MSK-76 scale. A different relation between building typologies and vulnerability classes is instead considered by the EMS-98, embedding an implicit probabilistic relation between building typologies and vulnerability classes.

In this work, the association of building typologies to vulnerability classes was carried out though a hierarchical agglomerative clustering strategy [22], based on the similarity of the observed seismic fragility of the building typologies. A matrix of inter-distances between building typologies is constructed and building typologies with shortest inter-distances are iteratively grouped into broader clusters, until three classes are obtained. Details of the implemented clustering strategy can be found in [23]. Table 2 shows the definition of vulnerability classes resulting from clustering, with colors denoting the level of seismic vulnerability: red refers to the class of higher vulnerability, yellow to the one of medium vulnerability, whilst green corresponds to the class of low vulnerability (C1). Buildings with irregular layout or poor-quality masonry belong to the class of higher vulnerability, with the only exception of those with rigid diaphragms and with connecting devices, belonging to vulnerability class B. On the other side, vulnerability class C1 includes buildings with regular layout and good-quality masonry, with the only exception of buildings with flexible diaphragms and without connecting devices, which in turn belong to the class of medium vulnerability (i.e. class B).

Empirical fragility curves were hence derived for the three vulnerability classes (i.e. A, B and C1), then refined based on the building height (i.e. low-rise (L): 1-2 stories and mid-/high-rise (MH): >2 stories), as depicted in Fig. 6.



Table 2 – Definition of vulnerability classes based on the adopted clustering strategy

| | Irregular layout or poor-quality (IRR) | | Regular layout and good-quality (REG) | |
|---|---|---|---|---|
| | No tie-rods/tie-beams (NCD) | Tie-rods and/or tie-beams (CD) | No tie-rods/tie-beams (NCD) | Tie-rods and/or tie-beams (CD) |
| Flexible (F) | A | A | B | C1 |
| Rigid (R) | A | B | C1 | C1 |

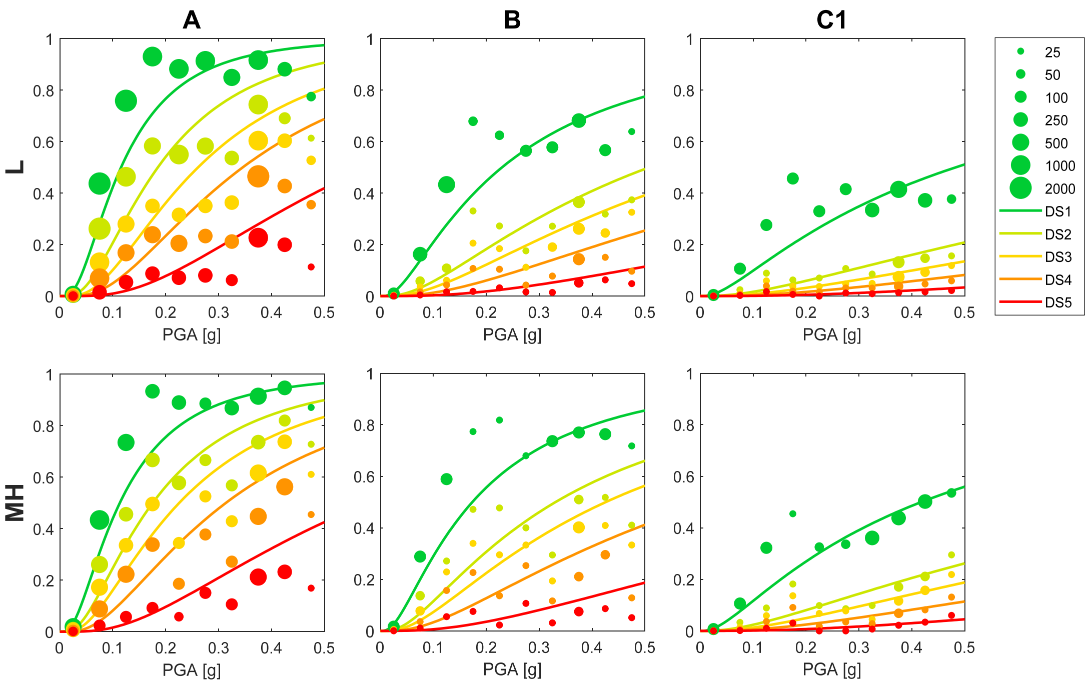



Fig. 6 – Empirical fragility curves for vulnerability classes (i.e. A: high vulnerability, B: medium vulnerability and C1: low vulnerability) and classes of building height (i.e. L: low-rise and MH: mid-/high-rise). Adapted from Rosti et al. [10]

## 4. Territorial seismic risk assessment: case-study application

The suitability of the proposed empirically-derived fragility model for large scale seismic risk evaluations is demonstrated through a case-study application, with reference to the Campania region (Fig. 7). To this aim, the fragility model discussed in Section 3 was implemented in the Italian national seismic risk platform [12], where seismic hazard is defined by the MPS04 seismic hazard model [24][25] and exposure is based on national census data [15].

Seismic vulnerability is described by using the fragility curves derived for vulnerability classes and classes of building height (Fig. 6) whereas building attributes considered by national census are construction material, building height and construction age. It was therefore necessary to define the composition of the exposed building stock in terms of predefined vulnerability classes, to associate the considered fragility curves to building categories, consistently defined with the information from national building census. The vulnerability classification of the exposed masonry building stock was carried out through a statistical approach based on post-earthquake damage data [23]. Fig. 8 shows the composition of the exposed masonry building stock in terms of percentages of masonry buildings belonging to the different vulnerability classes.



Seismic risk was quantified in terms of physical damage annually expected on the masonry building stock. The results obtained are reported in Fig. 9, in terms of regional seismic risk maps showing the geographical distribution of the percentages of masonry buildings exceeding preselected damage levels (from DS1 to DS5), in one year.

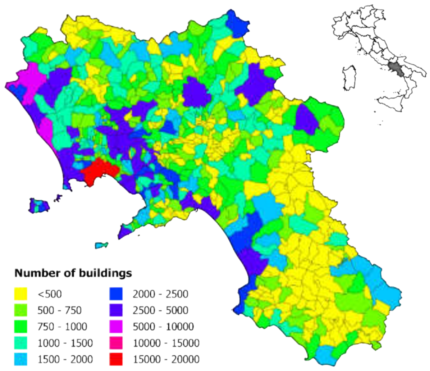
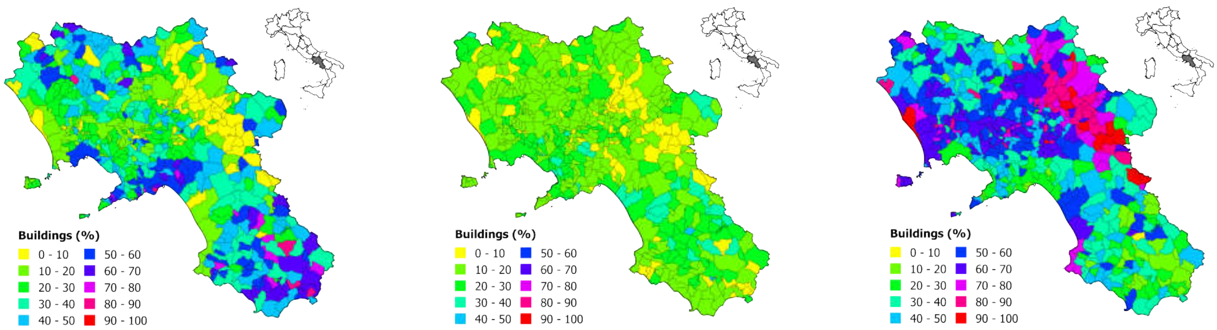



Fig. 7 – Exposure of the Campania region: number of masonry buildings per municipality [15]




(a) (b) (c)

Fig. 8 – Vulnerability classification of the masonry building stock of the Campania region: percentages of masonry buildings belonging to vulnerability class A (a), B (b) and C1 (c)

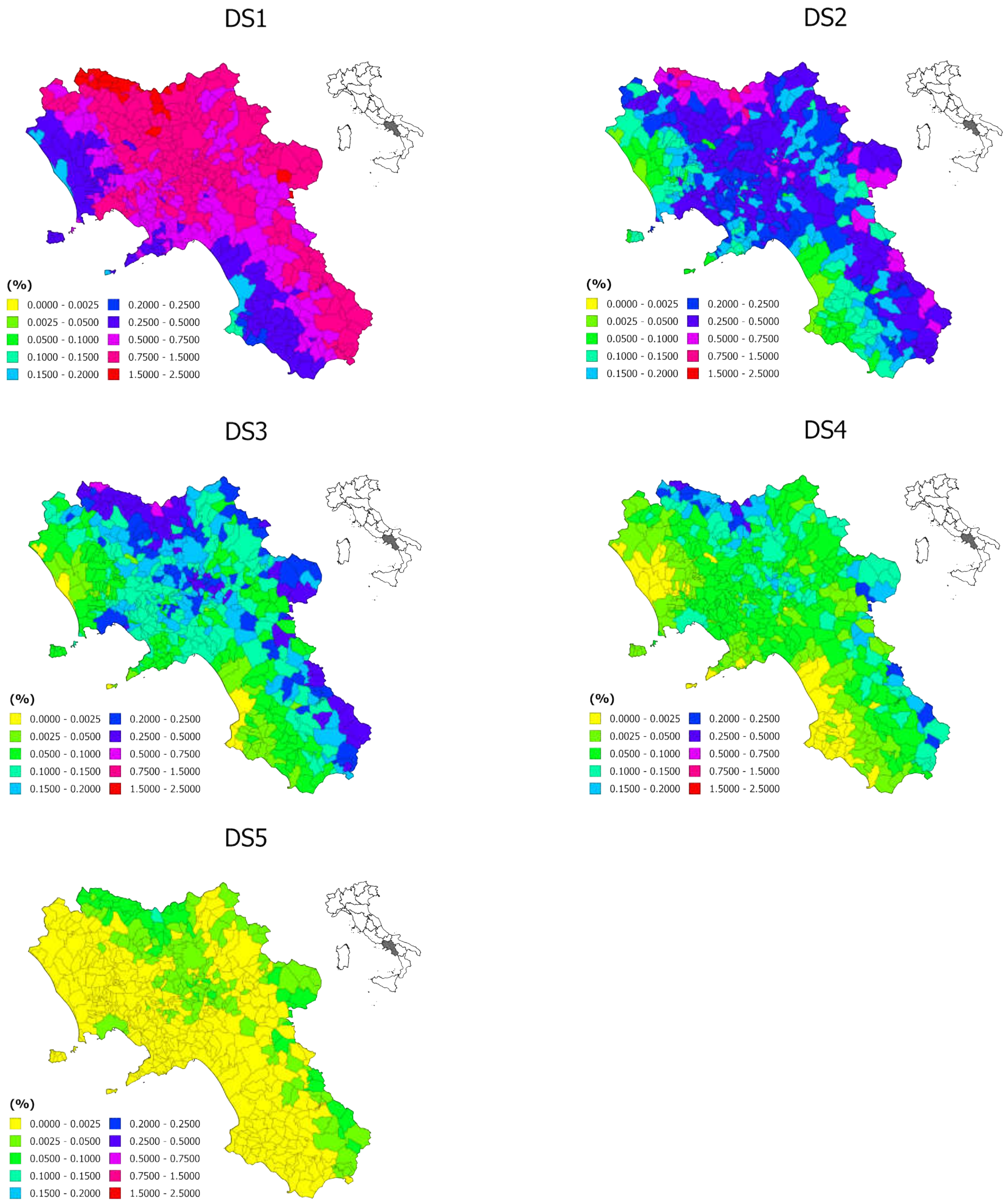



Fig. 9 – Maps of the expected percentages of masonry buildings exceeding different damage states (from D1 to DS5) in one year.

## 5. Conclusions

Empirical fragility curves for residential masonry buildings are derived by statistically processing Italian post-earthquake damage data collected in the time window 1980-2009. Fragility curves are first derived for eight building typologies, representative of the Italian building stock, and five levels of damage consistent with the EMS-98. The cumulative lognormal distribution is adopted to fit empirical data points, as a function of the peak ground acceleration, estimated via shakemap, representing the selected seismic intensity measure. The multinomial distribution is assumed to approximate the subdivision of buildings in the different damage levels, conditioned on the PGA. Three vulnerability classes of decreasing vulnerability are then defined, based on the similarity of the observed seismic fragility of building typologies. To this aim, a hierarchical agglomerative clustering strategy is set up, to objectively merge predefined building typologies into wider clusters, up to the definition of the three vulnerability classes. Empirical fragility curves are then derived in terms of vulnerability classes and two classes of building height. A case-study application, carried out by means of the Italian national seismic risk platform, is then illustrated to show the feasibility of the proposed empirical fragility model for territorial seismic risk evaluations.

## 6. Acknowledgements

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