EMPIRICAL FRAGILITY CURVES FOR ITALIAN RESIDENTIAL BUILDINGS

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Introduction. This study describes the derivation of empirical fragility curves for the Italian residential building stock based on the data recently published by the Italian Department of Civil Protection in the online platform Da.D.O. (Database di Danno Osservato, Dolce *et al*. 2017), collecting single-building post-earthquake damage data from Italian earthquakes. An application of the proposed fragility models to the Campania region is also presented.

Damage database. The Da.D.O. platform collects post-earthquake damage databases of nine seismic events occurred in Italy, from Friuli 1976 to Emilia 2012. On the whole, data on slightly more than 300.000 are available, with approximately 80% of masonry buildings, 8% of RC buildings and the remaining part made of other typologies. Among all of the abovementioned events, available data differ for type and detail of information on damage (e.g., assumed damage scale, presence or not of information on damage extent and/or on damage to nonstructural components).

The fragility analysis based on these data, as described below, employs an instrumental intensity measure (Peak Ground Acceleration, PGA) for the characterization of the seismic input. Therefore, only the events for which a shake map consistently derived with the INGV procedure (Michelini *et al.*, 2008) was available were considered. For RC buildings, only seismic events with damage data on structural and nonstructural (infill/partitions) components were selected. Furthermore, among these selected events, only those with damage data characterized by "complete" surveys were retained, in order to avoid possible biases in the estimation of seismic fragility due to the presence of non-surveyed (likely non-damaged) buildings.

Based on these criteria, the Irpinia (1980) and L'Aquila (2009) databases were employed only.

Description of complete damage datasets. About 77% of residential masonry buildings of the complete damage database, including data from these two seismic events, are made of irregular layout or poor-quality materials, whereas 23% are characterized by regular texture and good-quality masonry. Focusing on the Irpinia dataset, 89% and 11% of masonry buildings are low-rise (i.e. 1-2 stories) and mid-/high-rise (i.e. >2 stories), respectively. About 59% of residential masonry buildings of the L'Aquila dataset are low-rise, whereas 41% have more than 2 stories. More than 36% of the Irpinia masonry constructions date back prior to 1900, whereas about 50% of the L'Aquila masonry buildings were built before 1920.

As far as RC buildings are concerned, the great part of the buildings of Irpinia 1980 event, for which the information on the age of construction was available, was built after 1962, while for L'Aquila dataset about 35% of the buildings was built before 1981 and 65% after 1981. With regard to the number of stories, 65% of Irpinia dataset is between 1 and 2, 30% between 3 and 4, and 5% greater than 4, with a modal value of 2, whereas 28% of L'Aquila dataset is between 1 and 2, 61% between 3 and 4, and 10% greater than 4, with a modal value of 3.

Damage analysis. The definition of the damage scale represents a key issue of seismic fragility assessment (e.g. Rosti *et al.* 2018). In this work, damage states were defined consistently with the European Macroseismic Scale EMS-98 (Grünthal 1998). A global damage level was assigned to each inspected building, in accordance with the damage conversion rules proposed by Rota *et al.* (2008) and Del Gaudio *et al.* (2017), considering the maximum level of damage observed on preselected building components.

Derivation of typological fragility curves. The PGA was the selected ground motion intensity measure, estimated at the building locations by the INGV ShakeMaps (Michelini *et al.* 2008). The ground motion range was subdivided into equally-spaced bins of 0.05g width. Empirical damage data were approximated by fitting a lognormal cumulative distribution through the Maximum Likelihood Estimation (MLE) method. To ensure the ordinal nature of damage, a constant dispersion value for all damage states of a given building typology was assumed. The random component was described by the multinomial distribution (Charvet *et al.* 2014). In order to derive empirical fragility curves, building typologies were defined first, based on the selection of main building parameters influencing seismic fragility.

Typological fragility curves for masonry buildings. Fragility curves were derived for eight masonry building typologies, identified based on the layout and quality of the masonry fabric, in-plane flexibility of diaphragms and presence of connecting devices (e.g. tie-rods and tie-beams), consistently with the information reported in the damage survey forms.

Typological fragility curves for RC buildings. Fragility curves were derived for RC buildings by defining building typologies based on two parameters, namely the number of stories (from 1 to 5, including the vast majority of the buildings in the selected database) and the type of design (for gravity loads only, for seismic loads pre-1981 – deemed as "obsolete", and for seismic loads post-1981). Roughly speaking, data on buildings designed for gravity loads only or for seismic loads came from the Irpinia 1980 and L'Aquila 2009 event, respectively, because the vast majority of Municipalities hit by the Irpinia event were not yet classified as seismic in 1980, whereas most of the Municipalities hit by the L'Aquila event were classified as seismic since 1915 (R.D.L. 29/04/1915). The choice of a distinction between pre- and post-1981 buildings designed for seismic loads was based on a side on the evolution of technical codes (D.M. 03/03/1975) and, on the other side, on the need of consistency between the databases of the two events. The analysis of the damage suffered by these RC building typologies through vulnerability curves showed a clear hierarchy with increasing damage for buildings designed for gravity loads only, for seismic loads pre-1981 or for seismic loads post-1981, respectively. Then, fragility curves were derived for each one of these 15 (=5×3) typologies.

Class fragility curves for damage prediction based on census data. The fragility curves proposed in this study have to be applied starting from information on building characteristics provided by ISTAT census data. Therefore, consistent with this need, further fragility curves had to be derived, starting from the abovementioned typological fragility curves, for specific classes of buildings with characteristics that could be determined based on ISTAT census data.

Five fragility curves (i.e. A, B, C1, C2, D) were derived, three for masonry buildings and two for RC buildings, based on the procedure described below.

Class fragility curves for masonry buildings. Masonry building typologies were associated to vulnerability classes A, B and C1, of decreasing vulnerability. To this aim, the attribution of masonry building typologies to vulnerability classes was carried out through an agglomerative hierarchical clustering, up to the identification of the three classes, which were

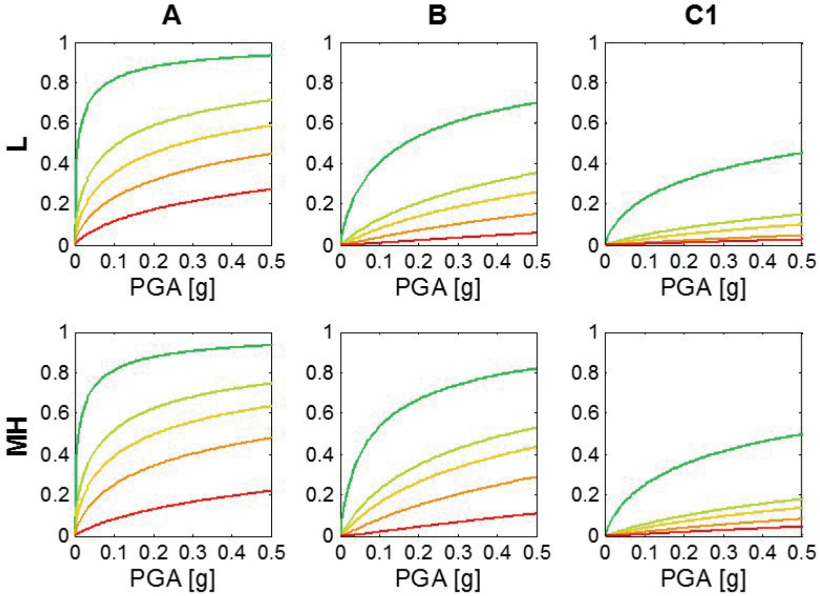


Fig. 1.

then subdivided based on the class of height (i.e. low-rise: 1-2 stories and mid-/high-rise: >2 stories), see Fig. 1. On the other side, empirical damage data were classified into macro-typologies, based on the information of the national census data (i.e. construction material, class of height and construction age). The vulnerability model was defined by determining the fractions of each macro-typology belonging to the predefined vulnerability classes. To this aim, the fragility curve of a preselected macro-typology and of a given damage state was expressed as a linear combination of the fragility curves of the vulnerability classes. The coefficients of the linear combination, representing the fractions of each macro-typology belonging to the predefined vulnerability classes, were obtained by solving an optimization problem.

Class fragility curves for RC buildings. Fragility curves for RC buildings were defined for two vulnerability classes, C2 and D, of decreasing vulnerability, and depending on the class of height. More specifically, buildings designed for gravity loads only or for seismic loads pre-1981 were

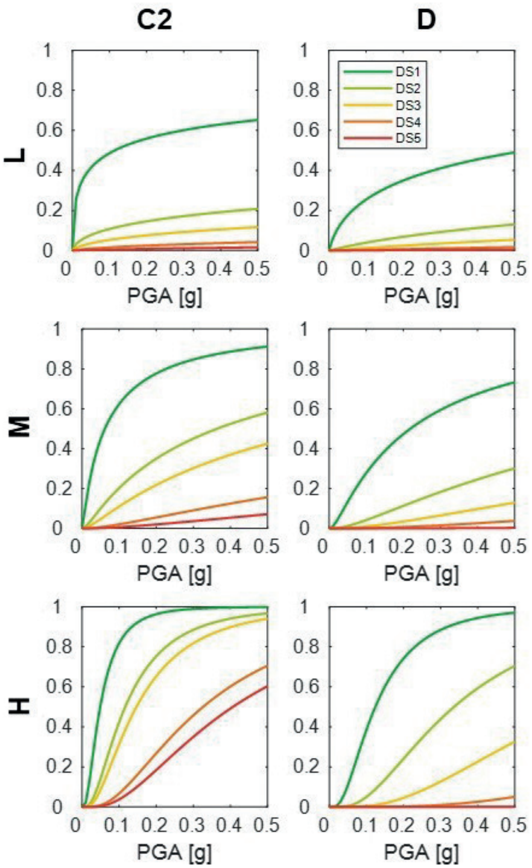
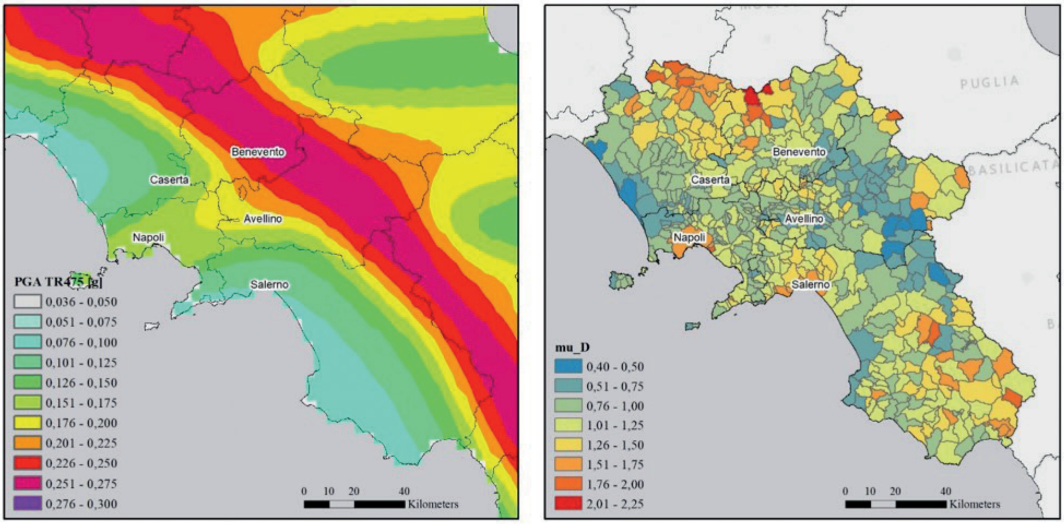


Fig. 2.



(a) (b)

Fig. 3.

grouped in class C2, whereas buildings designed for seismic loads post-1981 were assigned to class D. Moreover, these classes were further specialized to three ranges of height, i.e. low-rise: 1-2 stories, mid-rise: 3-4 stories, and high-rise: >4 stories (Fig. 2). To this end, these 6 (=3×2) sets of fragility curves were derived as a weighted average of the abovementioned 15 (=5×3) sets of typological fragility curves, using as weights the probabilities of occurrence of each typology within the corresponding class, evaluated based on ISTAT census data at national scale, consistent with the aim of national-scale applications.

Example of application to Campania (Southern Italy) region. This section presents an example of application with reference to the Campania region. The proposed fragility models were used to derive a damage scenario for the whole region. The scenario was derived with the PGA demand corresponding to a return period T_R=475 years (Fig. 3a). For the sake of clarity, for each Municipality the results are illustrated in terms of mean damage (μ_D), i.e. the weighted average of the DS index (from 0 to 5) within a given Municipality (Fig. 3b). The territorial distribution of μ_D roughly reflects the distribution of PGA intensity, as expected, except for some cases in the provinces of Avellino and Salerno, where a relatively lower μ_D value is observed in some Municipalities where the reconstruction process following the Irpinia 1980 event leads to a prevalence of class D buildings (i.e., post-1981 RC buildings designed for seismic loads).

Conclusions. In this study, data on observed post-earthquake damage provided by the by the Italian Department of Civil Protection through the online platform Da.D.O. were used to derive empirical fragility curves for classes of masonry and RC residential buildings. Damage States were assumed consistent with EMS-98 and damage data were processed accordingly. Fragility curves were derived for different building typologies and then for building classes, in accordance with the aim of a national-scale application based on census data. The availability of empirical data allowed the derivation of fragility curves that should reliably reflect the characteristics of the building stock they will be applied to.

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