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STATISTICAL TREATMENT OF EMPIRICAL DAMAGE DATA COLLECTED AFTER THE MAIN ITALIAN SEISMIC EVENTS (1980-2009)

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Abstract

Since the number of victims and the amount of economic losses are closely related to the seismic performance of structures, in the last decades significant relevance has been addressed to the evaluation of the seismic vulnerability of existing buildings. In this context, empirical damage data, collected during post-earthquake field surveys, constitute a very precious patrimony, being a valuable and unique source of information that should be fully exploited. With proper treatment and accurate processing, they can indeed provide an excellent picture of the real vulnerability of existing buildings and, in this sense, they may also represent a benchmark for calibrating numerical vulnerability models. This paper deals with the derivation of damage probability matrices for structural typologies representative of the Italian building stock, starting from empirical damage data collected after the Italian seismic events of the period 1980-2009. After processing and homogenization, empirical data were subdivided into building typologies, representative of the Italian building stock, and damage levels of a previously defined damage scale. A measure of the ground-motion severity was associated to each inspected building. For each identified building typology, damage probability matrices were subsequently derived for different levels of ground motion severity.

Keywords: seismic vulnerability, post-earthquake field surveys, existing buildings, L'Aquila seismic event (2009), damage probability matrices

1. Introduction

Empirical data, collected during post-earthquake field surveys, represent a sort of *in situ* test of the vulnerability of the existing building stock, as observed data are, at least theoretically, the most realistic source of information. Indeed, they implicitly account for all the characteristics of both ground motion and building stock. Nonetheless, similarly to *in situ* tests on structural elements, *in situ* conditions, despite representing reality, are not as well controlled as laboratory conditions. Therefore, the interpretation of the obtained information often results tricky and controversial. Despite these limitations, post-earthquake data, representing a realistic and invaluable source of information on the vulnerability of the building stock, should be used for several applications, such as for the improvement of alternative approaches for the derivation of fragility curves.

A practical method for estimating the seismic vulnerability of building typologies or building classes consists in defining damage probability matrices (DPMs) [1]. For a given building class and intensity level, a damage probability matrix represents the damage distribution in the different damage levels. Although observed damage data represent the most realistic source of information, if collected after a single earthquake they may be scanty and/or may not cover a sufficiently wide range of ground motion intensity. To make up for data scarcity and increase the available dataset, previous works assembled damage data from different earthquakes occurred in the same (e.g. [2]) or in different countries (e.g. [3]). Nonetheless, when multiple databases are aggregated, data from areas with similar tectonic environments and for the same structural typologies should be considered [4]. Moreover, data heterogeneity may represent a possible limitation of this approach. The uncertainty introduced by aggregating multiple databases is reduced if the selected databases consider, for instance, the same damage scale and building classification. Nevertheless, damage assessment might be carried out by using different post-earthquake survey forms, evolving in time, even in the same country. In these cases, an intermediate process of data homogenization is required to subdivide damage data in similar building classes and damage levels. Along these lines, this work presents the statistical analysis of an updated damage database, approximately boasting 142000 data. Damage data collected after the L'Aquila earthquake of 2009 are processed and then added to post-earthquake data collected after the main Italian earthquakes of the period 1980-2002 ([2], [5]). For different building typologies representative of the Italian building stock, damage probability matrices are then derived.

2. Analysis of empirical data collected after L'Aquila earthquake (2009)

This Section presents the analysis of damage data collected during post-earthquake surveys after L'Aquila (2009) seismic event. Buildings inspections were carried out through the first level form for post-earthquake damage assessment, short term countermeasures and usability assessment of ordinary buildings, called AeDES form [6], oriented to survey typological, damage and usability characteristics of residential buildings in the emergency phase in the aftermath of a seismic event. The L'Aquila database included survey forms of about 73000 buildings located in 129 municipalities. In this work, data processing was carried out according to the hypotheses of Rota et al. [2], in order to allow integration of the damage data with those of previous Italian events (1980-2002). In particular, the development of damage probability matrices requires the characterization of the seismic input, the identification of structural typologies, and the definition of damage levels. All these three aspects are discussed in the following.

2.1 Seismic input characterization

Peak ground acceleration (PGA) was selected for describing the severity of the ground shaking. Each municipality hit by the earthquake was treated as an isoseismic unit, characterized by a unique value of PGA, assumed to correspond to the mean value over the territory of interest. For each municipality, the PGA was evaluated on rock by means of the Sabetta and Pugliese [7] attenuation law, in accordance with [5]. Fig.1 (left) shows the subdivision of the municipalities in ten PGA bins. On the right, the inspected buildings are subdivided in the ten PGA intervals. It is observed that the substantial number of buildings in the PGA interval 0.4-0.5g derives from buildings located in the municipality of L'Aquila.

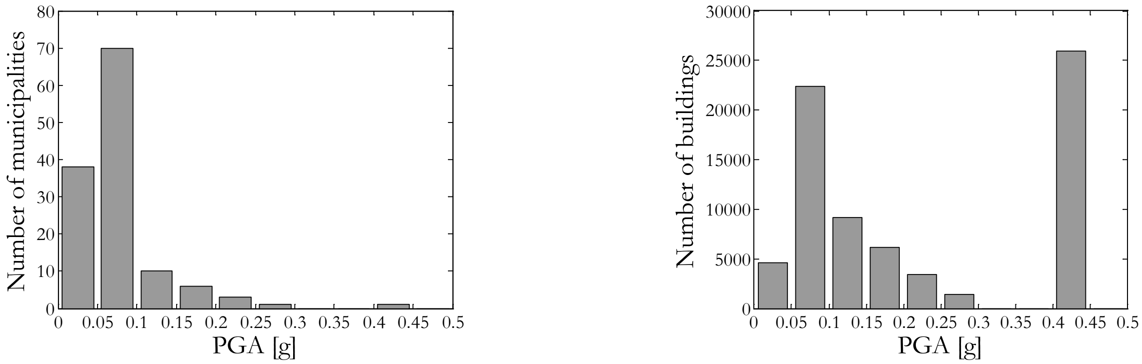

Fig. 1 – Number of municipalities per PGA interval (left) and number of inspected buildings per PGA interval (right)

2.2 Identification of building typologies

Damage probability matrices are defined for building typologies or classes, defined by grouping buildings with similar seismic performance. The choice of the number of structural typologies to be considered derives from a compromise between usability and accuracy. A detailed subdivision into building typologies allows to obtain very specific results, but an extremely detailed classification may lead to a significant reduction of the sample size, consequently affecting the reliability of the estimated damage distributions. Differently, broader and coarser categories could include buildings with different seismic performance, leading to an average estimate of the seismic vulnerability, which is not representative of any specific building typology. In this work, buildings were first classified based on the type of vertical bearing structure, namely masonry, reinforced concrete (RC), mixed structure (i.e. masonry and reinforced concrete) and steel, in accordance with [2]. In the case of steel constructions, no further subdivisions were defined, given the limited number of buildings. In the case of mixed structures, two subcategories were introduced, based on the number of stories above the ground level (Table 1). Reinforced concrete buildings were further subdivided depending on the number of stories and period of construction. This last information, together with the year of seismic classification of the municipality where the building is located, allows to establish if a building was designed and built according to seismic prescriptions or not. In particular, RC buildings were considered to be "seismically designed" if built after year 1975, in a municipality already classified as "seismic" at the time of construction of each building. Year 1975 was selected as reference year as corresponding to the first applicative decree of the Italian law No. 64 of 1974, introducing a new seismic classification and specifying new prescriptions for structures in seismic areas. Masonry buildings were classified according to the layout and quality of the masonry. In particular, irregular masonry buildings (i.e. buildings with irregular layout or poor quality masonry) were distinguished from regular masonry buildings (i.e. masonry buildings with regular layout and good quality masonry). Further subdivisions were carried out based on the type of horizontal structure (i.e. rigid or flexible), the number of stories and the presence or absence of tie-rods and tie-beams.

The AeDES survey form allows multiple choice for defining the type of vertical and horizontal structures of a masonry building. In order to associate a single structural typology to each surveyed building, the following criteria were considered. Regarding the attribution of the vertical bearing structure, in the case of equal number of occurrence, irregular masonry prevails on regular masonry, as more vulnerable. The presence of tie-rods and/or tie-beams prevails on the absence, as, even if few, these elements are present. Concerning the horizontal structure, in the case of equal number of occurrence, rigid floors prevail on flexible floors as they tend to govern the building seismic response. The twenty-three identified building typologies are listed in Table 1.

2.3 Damage scale

In post-earthquake survey forms, the degree of severity of the apparent damage observed during inspections is mainly expressed in terms of type and extent of damage. A suitable correlation between damage description and a preselected damage scale is hence required. In accordance with [5], a damage scale based on the European

Macroseismic scale, EMS-98 [8], was adopted. The selected damage scale is characterized by five damage levels (i.e. DS1, DS2, DS3, DS4 and DS5), plus the case of no damage (DS0).

Table 1 – Identification of the selected building typologies

Label	**Building typology**	**No. of stories**
MX1	Mixed	1-2
MX2	Mixed	≥3
RC1	Reinforced Concrete – Seismic Design	1-3
RC2	Reinforced Concrete – No Seismic Design	1-3
RC3	Reinforced Concrete – Seismic Design	≥4
RC4	Reinforced Concrete – No Seismic Design	≥4
IMA1	Masonry – Irregular Layout – Flexible floors – with tie-rods and/or tie-beams	1-2
IMA2	Masonry – Irregular Layout – Flexible floors – w/o tie-rods and tie-beams	1-2
IMA3	Masonry – Irregular Layout – Rigid floors – with tie-rods and/or tie-beams	1-2
IMA4	Masonry – Irregular Layout – Rigid floors – w/o tie-rods and tie-beams	1-2
IMA5	Masonry – Irregular Layout – Flexible floors – with tie-rods and/or tie-beams	≥3
IMA6	Masonry – Irregular Layout – Flexible floors – w/o tie-rods and tie-beams	≥3
IMA7	Masonry – Irregular Layout – Rigid floors – with tie-rods and/or tie-beams	≥3
IMA8	Masonry – Irregular Layout – Rigid floors – w/o tie-rods and tie-beams	≥3
RMA1	Masonry – Regular Layout – Flexible floors – with tie-rods and/or tie-beams	1-2
RMA2	Masonry – Regular Layout – Flexible floors – w/o tie-rods and tie-beams	1-2
RMA3	Masonry – Regular Layout – Rigid floors – with tie-rods and/or tie-beams	1-2
RMA4	Masonry – Regular Layout – Rigid floors – w/o tie-rods and tie-beams	1-2
RMA5	Masonry – Regular Layout – Flexible floors – with tie-rods and/or tie-beams	≥3
RMA6	Masonry – Regular Layout – Flexible floors – w/o tie-rods and tie-beams	≥3
RMA7	Masonry – Regular Layout – Rigid floors – with tie-rods and/or tie-beams	≥3
RMA8	Masonry – Regular Layout – Rigid floors – w/o tie-rods and tie-beams	≥3
ST	Steel	≥1

The identified damage levels consist of DS0 - no damage, DS1 - negligible/slight damage, DS2 - moderate damage, DS3 - severe damage, DS4 - very severe damage, DS5 - collapse. In order to attribute a damage level to each inspected building, only structural damage was considered, defined as the maximum damage observed among vertical bearing structure, horizontal structure and roof. The information of non-structural damage was only considered for distinguishing cases of incomplete survey forms from the cases of null structural damage. In the absence of information on structural damage, if information on non-structural damage was reported in the form, structural damage was considered null. Conversely if no information on non-structural damage was provided, this was considered a case of incompletely-filled form and the damage level was considered unidentified.

2.4 Analysis of the available data

Due to the presence of incomplete surveys forms or to the lack of important information, the total number of buildings considered in the final database was subsequently reduced. This type of errors is mainly due to the large number of buildings to be inspected in few days and to the rapidity of the same field surveys [9]. In this work, buildings with important information partially or totally missing were discarded. In particular, buildings for which the type of vertical structure, the type of horizontal structure (in the case of masonry buildings), the number of stories and the observed damage level were missing were excluded. Following this analysis, approximately 10% of the initial data were discarded.

2.4.1 Issue of completeness of field surveys

The incompleteness of post-earthquake surveys can lead to a systematic bias in the damage distribution resulting from the statistical analysis of empirical data. This issue typically arises in the case of sites more distant from the epicentre, where it is likely that only buildings whose inspection was requested by the owner were surveyed. A common practice to avoid such a bias in the resulting damage distributions consists in defining a minimum threshold of completeness, that is a minimum percentage of inspected buildings within a given isoseismic unit. If the proportion of inspected buildings within the unit is less than the selected threshold of completeness, field surveys are deemed incomplete over the territory of interest. Conversely, if a percentage of the building stock larger than the selected threshold of completeness is inspected, the isoseismic unit is assumed to be entirely surveyed. In order to define a complete dataset previous works selected different thresholds of completeness. For instance, Rota et al. [2] assumed a proportion of completeness equal to 60%, Sabetta et al. [10] equal to 75%, whereas Goretti and Di Pasquale [11] of 80%. According to Dolce et al. [12], sites, either municipalities or hamlets, with an associated macroseismic intensity exceeding 6 [13], were completely surveyed after the L'Aquila earthquake. Nonetheless, in this work, all the municipalities with a threshold of completeness at least equal to 60% were identified in order to integrate these damage data with those processed by Rota et al. [2], using consistent assumptions on completeness. For each municipality, the number of inspected buildings was compared to the number of buildings provided by the national census data [14]. The municipalities of Calascio and Castel del Monte were excluded as the number of inspected buildings was significantly larger than the number indicated by ISTAT [14], hence suggesting the presence of possible double or multiple surveys. The resulting dataset, corresponding to a threshold of completeness equal to 60%, includes 50865 buildings. Subdivision of data based on the type of vertical structure and among the different building typologies is shown in Fig.2 left and right, respectively.

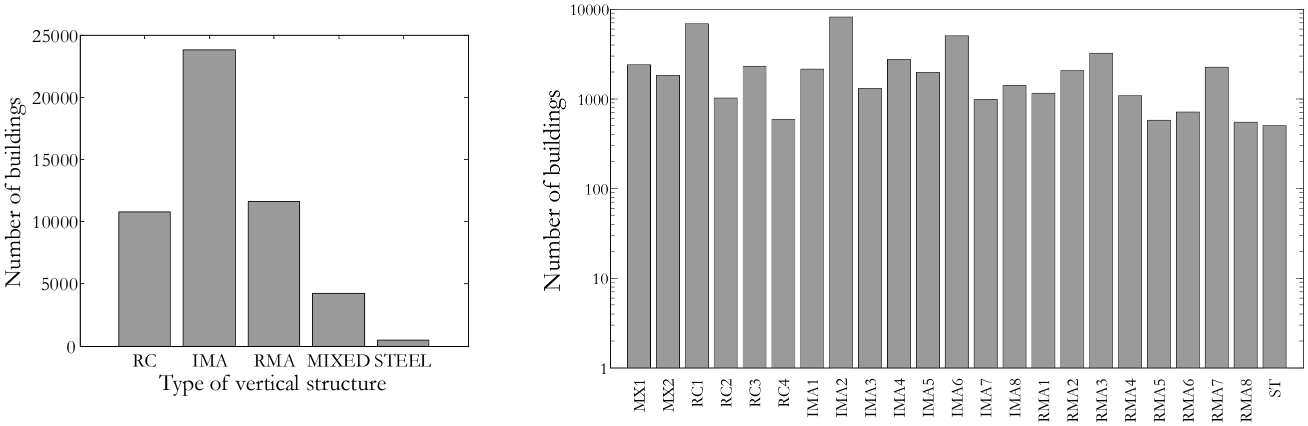

Fig. 2 – Subdivision of data based on the type of vertical structure (left) and among the selected building typologies (right) – L'Aquila "complete" database (60% completeness)

3. Statistical analysis of damage data collected after the main Italian earthquakes (1980-2009)

Once processed, L'Aquila damage data were added to post-earthquake survey data collected after the main Italian earthquakes of the period 1980-2002 [2]. Aim of this work was to create an updated database, larger than the one used by Rota et al. [2] and improved by the addition of a substantial number of buildings at higher PGA levels (Fig.1). Table 2 lists the seismic events considered for the creation of the integrated database, together with their main characteristics retrieved from the parametric catalogue of Italian earthquakes [15] and from the Italian seismological and instrumental database [16]. In the table, *M* indicates the value of magnitude considered in the selected attenuation law. In the case of L'Aquila seismic event, it was assumed the equivalence between the value of magnitude reported by ISIDe [16] and the value to be used in the attenuation law, as suggested in Sabetta [17].

Table 2 – Main characteristics of the considered earthquakes for the creation of the aggregated database [15, 16]

Earthquake	**Year**	**Lat$_{Epc}$**	**Long$_{Epc}$**	**M**
Irpinia	1980	40.85	15.28	6.89
Abruzzo	1984	41.666	14.057	5.67
Umbria-Marche	1997	43.019	12.879	5.95
Pollino	1998	40.038	15.937	5.35
Molise	2002	41.694	14.925	5.59
L'Aquila	2009	42.342	13.38	6.1

The integrated database, corresponding to a threshold of completeness equal to 60%, includes 142259 buildings. Fig.3 shows the contribution of each earthquake in terms of number of buildings per PGA interval (left) and for different types of vertical structure (right), respectively. It is observed that data with PGA exceeding 0.3g correspond to buildings surveyed after the Irpinia (1980) and L'Aquila (2009) seismic events, only. In particular, a significant number of buildings in the PGA interval 0.4-0.5g derives from L'Aquila earthquake. The addition of L'Aquila data hence allowed the extension of the range of the available empirical data, previously statistically significant up to 0.3g and now up to 0.5g. However, these results were obtained by applying the Sabetta and Pugliese [7] attenuation law for the definition of the seismic input; therefore, they may change if a different (more recent) attenuation relationship is considered. It is also observed the significant increase of the number of RC buildings due to the addition of L'Aquila damage data. The subdivision of buildings in the twenty-three identified building typologies is depicted in Fig.4.

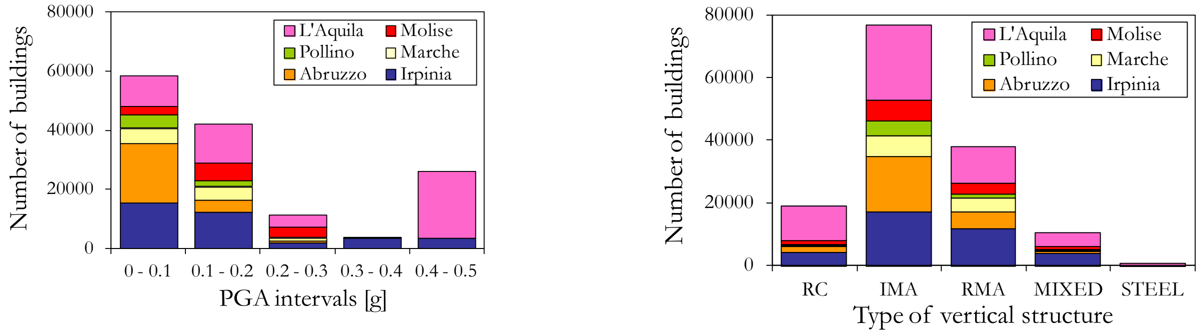

Fig. 3 – Number of buildings versus PGA interval (left) and type of vertical structure (right) with the identification of data from the different earthquakes

Damage probability matrices were then derived starting from the complete dataset. For each building typology and PGA interval, the number of buildings with a given damage level was computed. The probability of occurrence of each damage level was then derived by dividing the number of buildings of each damage level by the total number of buildings in the considered PGA bin. Fig.5, Fig.6 and Fig.7 show damage probability matrices for each building typology and five PGA intervals. DPMs of some masonry building typologies, particularly typologies with irregular layout or poor quality masonry, show the predominance of the probability of occurrence of damage level DS1, with respect to the probabilities associated with the other damage levels, irrespectively of the ground motion intensity level. This could be explained by the presence of pre-existing damage, that is damage prior to the damaging earthquake, due to bad maintenance conditions, as often observed in the oldest and most vulnerable masonry constructions. Empirical damage distributions also show the low seismic vulnerability of regular masonry buildings, particularly in the case of the presence of tie-rods and/or tie-beams. This is in agreement with evidence observed during post-earthquake reconnaissance surveys after previous events, such as the 1992 Erzincan earthquake [18] and the Emilia earthquakes (2012) [19].

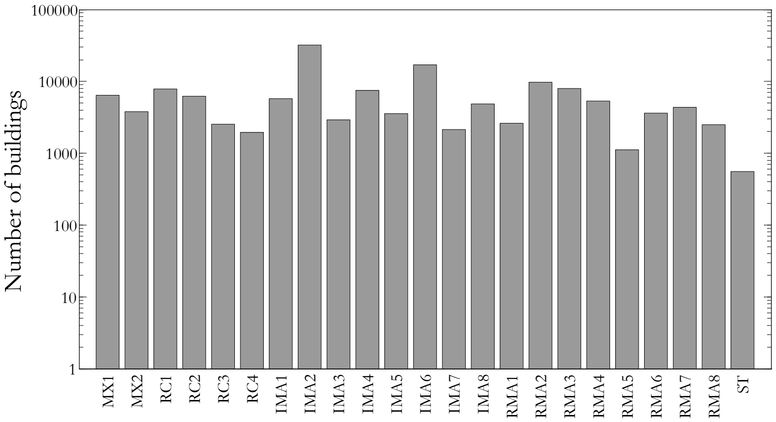

Fig. 4 – Subdivision of the buildings among the different building typologies – integrated database (60% completeness)

Comparison of DPMs of RC buildings shows that, as expected, non-seismically designed reinforced concrete buildings are generally more vulnerable than those seismically designed. Similarly, RC structures with more than three stories are more vulnerable than low-rise reinforced concrete buildings. Despite the significant amount of data, rather uniformly distributed in the PGA range 0-0.5g, for some building typologies data are incomplete or even missing, especially in the PGA bin 0.3-0.4g. This limitation, representing a possible issue when deriving empirical fragility curves, could be overcome or at least reduced by introducing a more accurate definition of the seismic input. Instead of being defined at the municipality level, the ground motion severity could be for instance defined building-by-building. To this aim, georeferenced data are required.

In addition to being a practical and direct way for estimating the seismic vulnerability, DPMs also represent the starting point for deriving empirical fragility curves. To this aim, the experimental probabilities of a given building typology and PGA interval are first cumulated from the highest to the lowest damage level. As an example, cumulative probabilities of building typologies MX1, IMA1 and IMA6 are shown in Fig.8, which shows a general tendency of damage to increase with an increase of the ground motion intensity.

4. Conclusions

In this preliminary work, DPMs for building typologies representative of the Italian building stock were derived by using empirical post-earthquake damage data collected after the Italian seismic events of the period 1980-2009. Damage probability matrices were derived from a huge database, boasting about 142000 data, that can be reasonably considered homogeneous, as all data were collected in Italy. In particular, the addition of L'Aquila damage data to data previously processed [2] allowed to extend the range of validity of the observed data from 0.3g to 0.5g.

DPMs of several masonry building typologies, particularly those with irregular layout or bad quality masonry, showed pre-existing damage. Differently, masonry buildings with regular layout and good quality masonry showed low seismic vulnerability, in agreement with post-earthquake field surveys carried out in the aftermath of other seismic events [18, 19]. Despite the significant number of buildings, empirical data resulted to be incomplete or even missing, especially in the PGA range 0.3-0.4g. However, this critical aspect could be overcome by introducing a more accurate definition of the seismic input. In order to counteract possible issues due to incomplete or missing data in some PGA bins, in the future, the characterization of the ground motion shaking will be carried out by considering more recent ground motion prediction equations (e.g. [20]).

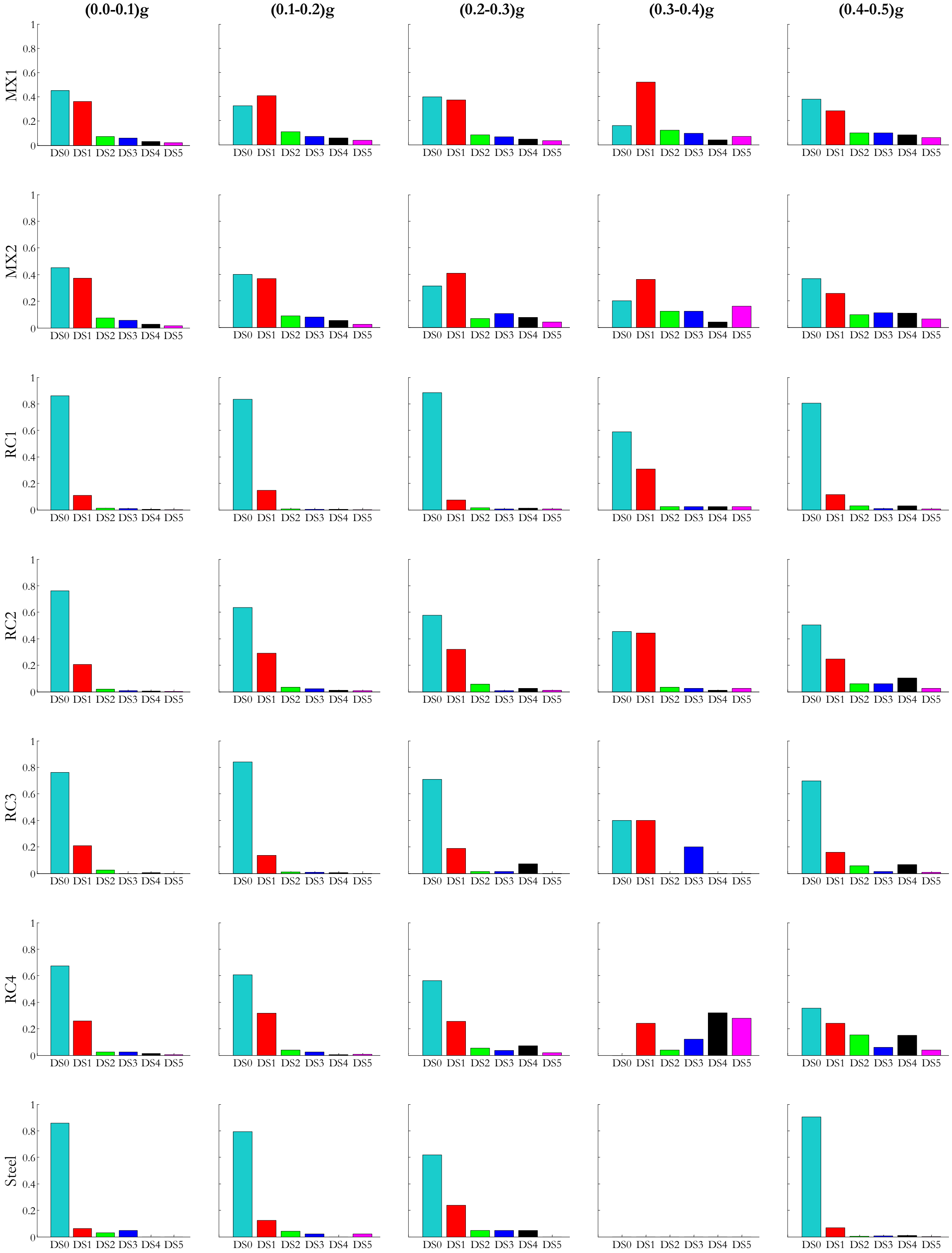

Fig. 5 – DPMs of building typologies: MX1, MX2, RC1, RC2, RC3, RC4, ST

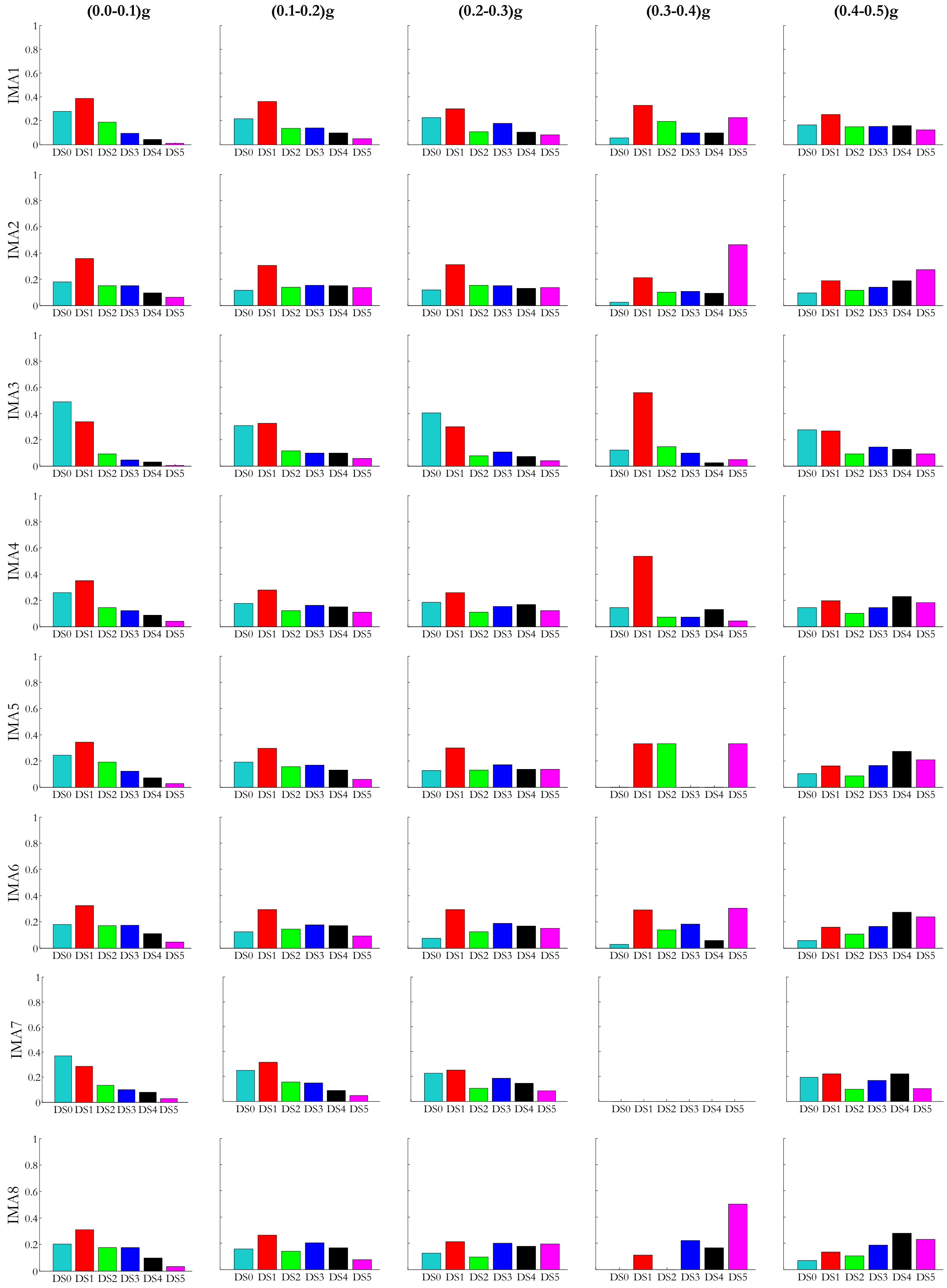

Fig. 6 – DPMs of irregular masonry building typologies

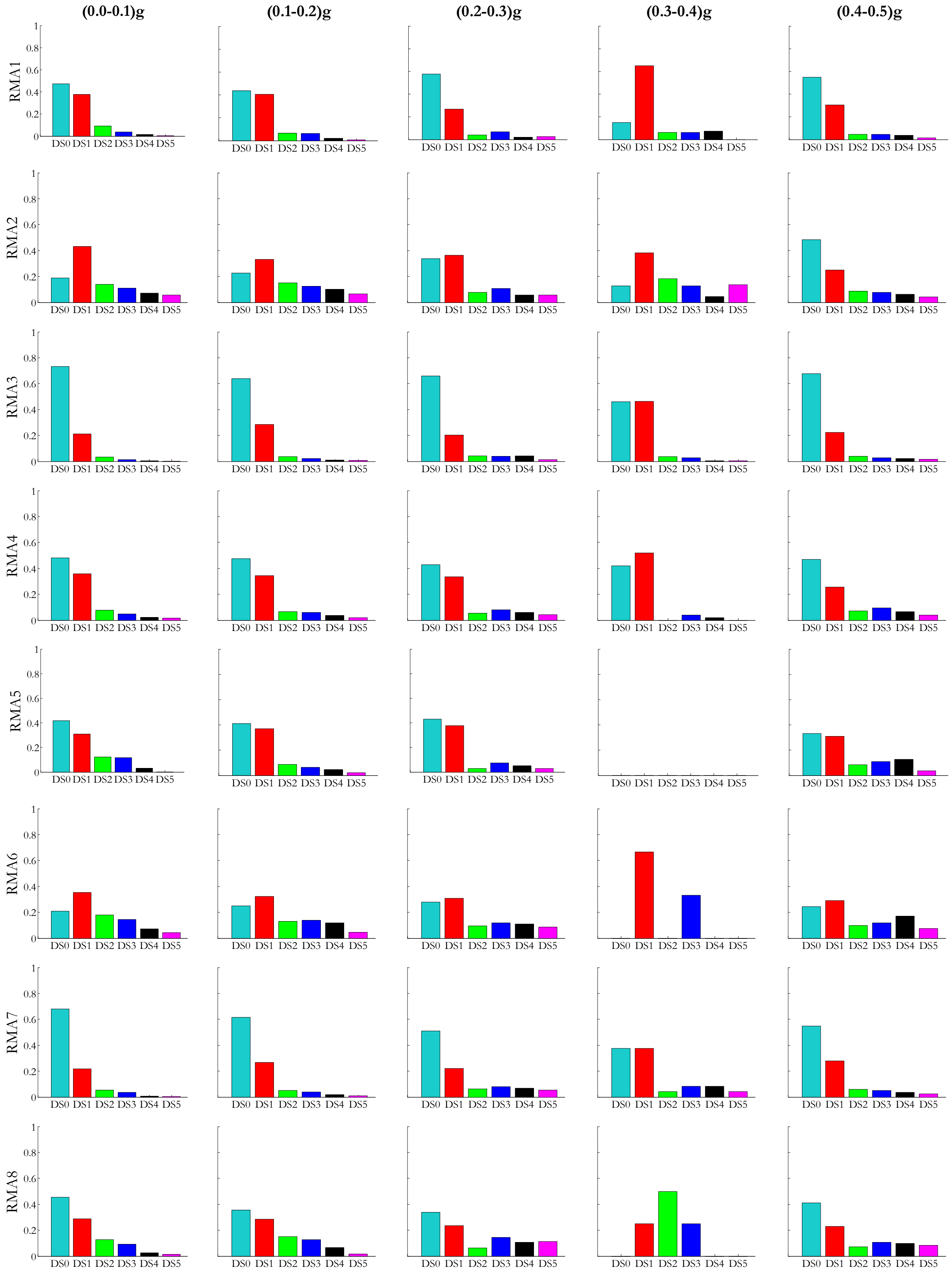

Fig. 7 – DPMs of regular masonry building typologies

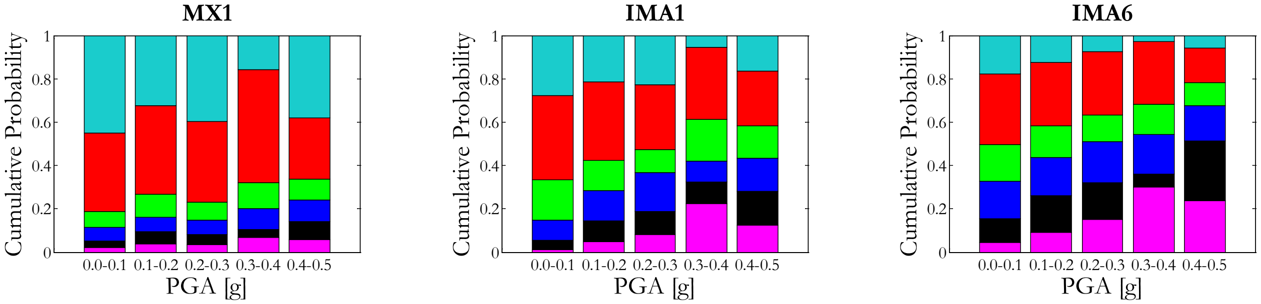

Fig. 8 – Cumulative probability for five PGA intervals – building typologies MX1, IMA1 and IMA6 – integrated database (60% completeness)

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6. 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. *Proceedings of the 7th European Conference on Earthquake Engineering*, Athens, Greece.

[2] Rota M, Penna A, Strobbia C (2008): Processing Italian damage data to derive typological fragility curves. *Soil Dynamics and Earthquake Engineering*, **28**(10-11), 933-947.

[3] Rossetto T, Elnashai A (2003): Derivation of vulnerability functions for European-type RC structures based on observational data. *Engineering Structures*, **15**, 1241-1263.

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

[5] Rota M, Penna A, Strobbia C, Magenes G (2008): Derivation of empirical fragility curves from Italian damage data. *Research Report No. ROSE-2008/08*, IUSS Press, Pavia, Italy.

[6] Baggio C, Bernardini A, Colozza R, 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 (AeDES). Translation from Italian: Goretti A, Rota M. *JRC Scientific and Technical Reports, EUR 22868 EN-2007*.

[7] Sabetta F, Pugliese A (1987): Attenuation of peak horizontal acceleration and velocity from Italian strong-motion records. *Bulletin of Seismological Society of America*, **77**(5), 1491-1513.

[8] Grünthal G (ed.), Musson RMW, Schwarz J, Stucchi M (1998): European Macroseismic Scale 1998. *Cahiers du Centre Européen de Géodynamique et de Séismologie*, **15**, Luxembourg.

[9] 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.

[10] Sabetta F, Goretti A, Lucantoni A (1998): Empirical fragility curves from damage surveys and estimated strong ground motion. *Proceedings of the 11th European Conference on Earthquake Engineering*, Balkema, Rotterdam.

[11] Goretti A, Di Pasquale G (2004): Building inspection and damage data for the 2002 Molise, Italy, earthquake. *Earthquake Spectra*, **20**(S1), S167-S190.

[12] Dolce M, Di Pasquale G, Albanese V, Benedetti D, Bramerini F, Coppari S, Corina A, De Rosa G, De Sortis A, Emili P, Ferlito R, Filippi L, Giordano F, Goretti A, Lo Presti T, Lucantoni A, Mercuri M, Moroni C, Orlandi N, Paoli G, Papa F, Pizza A, Procida F, RInaldelli M, Sergio S, Severino M, Speranza E, Veschi A, Zambonelli E, Manfredi G, Di Ludovico M, Palermo G, Prota A, Verderame G, Corazza L, Cifani G, Mannella A, Martinelli A (2009): Rilievi speditivi: sopralluoghi per l'agibilità sismica. *Progettazione Sismica*, **3**, IUSS Press – in Italian

[13] Galli P, Camassi R (eds. (2009): Rapporto sugli effetti del terremoto aquilano del 6 aprile 2009. *Joint Report DPC-INGV*, available at http://quest.ingv.it/images/quest/pubblicazioni/macrodef_sito.pdf - in Italian

[14] Census data (2001). Available at http:/dawinci.istat.it/jsp/MD/dawinciMD.jsp.

[15] Gruppo di lavoro CPTI (2004). Catalogo Parametrico dei Terremoti Italiani, versione 2004 (CPTI04), INGV, Bologna, DOI: 10.6092/INGV.IT-CPTI04.

[16] Italian Seismological Instrumental Parametric Database. Available at http://iside.rm.ingv.it.

[17] Sabetta F (2011): Abruzzo earthquake of April 2009: seismic sequence, ground motion attenuation, simulation scenario and losses. *Bollettino di Geofisica Teorica ed Applicata*, **52**(3), 427-442.

[18] Saatcioglu M, Bruneau M (1993): Performance of structures during 1992 Erzincan earthquake. *Canadian Journal of Civil Engineering*, **20**, 305-325.

[19] Penna A, Morandi P, Rota M, Manzini CF, Da Porto F, Magenes G (2014): Performance of masonry buildings during the Emilia 2012 earthquake. *Bulletin of Earthquake Engineering*, **12**(5), 2255-2273.

[20] Bindi D, Massa M, Luzi L, Ameri G, Pacor F, Puglia R, Augliera P (2014): Pan-European ground-motion prediction equations for the average horizontal component of PGA, PGV and 5%-damped PSA at spectral periods up to 3.0s using the RESORCE dataset. *Bulletin of Earthquake Engineering*, **12**, 391-430.