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EXPLORING THE EFFECT OF DIFFERENT DAMAGE DEFINITIONS ON THE EMPIRICAL BUILDING VULNERABILITY

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ABSTRACT

The association of global damage levels to buildings inspected during post-earthquake surveys is essential for deriving empirical damage distributions, representing, for a given building typology and ground motion intensity level, the repartition of damage in the different states. Furthermore, damage is a key ingredient of consequence functions and loss assessment procedures. Existing approaches commonly assess damage for individual building components and then consider their average or maximum value for the overall damage classification. Both the procedures require the selection of a predefined damage scale together with the definition of a suitable damage rule, converting the information on damage reported in the survey form into discrete damage states. Taking advantage of a complete and homogeneous damage database, compiled after the 2009 L'Aquila (Italy) earthquake, this study examines the effect of different damage classifications on the empirical building vulnerability. Two innovative hybrid procedures, both exploiting the binomial model, are proposed to account for the singular repartition of damage in the different states, observed in several building typologies. The feasibility of each approach is illustrated with reference to a case study.

Keywords: Empirical seismic vulnerability; Post-earthquake damage data; Damage probability matrices; Binomial distribution; L'Aquila (2009) seismic event

1. INTRODUCTION

Depending on the nature of the available data, existing approaches for the seismic vulnerability assessment are commonly classified into empirical, analytical, expert-judgmental and hybrid. In this framework, empirical damage data, collected during post-earthquake field surveys, are a valuable source of information, since representing a direct evidence of the actual buildings' response under real earthquakes. Several sources of uncertainty are associated with the acquired data and they need to be accounted for to provide a reliable and accurate description of the seismic vulnerability. Uncertainties are mainly related with survey conditions, such as the need of inspecting a large number of constructions in a short time, the presence of surveyors with different skills and expertise and the issue of survey incompleteness.

Empirical seismic vulnerability is commonly assessed in terms of damage probability matrices (DPMs), representing the damage distribution in the different states, conditioned on a given ground motion intensity level and building typology (e.g. Whitman et al. 1973; Braga et al. 1982), and fragility curves, continuously correlating the observed seismic damage and the ground motion shaking (Rossetto and Elnashai 2003; Rota et al. 2008; Pomonis et al. 2014; Del Gaudio et al. 2017). The evaluation of damage distribution due to a seismic event and the influence of different building components on the seismic vulnerability attract both scientists and practitioners. Structural engineers are mainly interested in the buildings' seismic performance to verify design assumptions and the adequacy of existing building codes. On the other hand, insurance companies primarily care about monetary aspects and exploit damage data to derive precious information on the vulnerability of

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different construction types, contributing to refine earthquake insurance rates.

Besides the ground motion characterization and the selection of a typological classification system, the derivation of damage probability matrices and fragility curves needs the definition of damage levels. The association of a global damage level to each inspected building is not immediate and requires the selection of a damage scale and appropriate damage conversion rules.

This study explores the impact of different damage descriptions on the empirical seismic vulnerability of building typologies representative of the Italian building stock, taking advantage of a complete and homogeneous damage database, collected in the aftermath of the 2009 L'Aquila (Italy) seismic event. Two hybrid procedures are proposed to interpret the results obtained in terms of damage probability matrices, showing the bimodal tendency of damage to distribute in the different levels. The feasibility of each approach is hence demonstrated with reference to a case study.

2. DESCRIPTION OF THE DAMAGE DATABASE

This study exploits a large and homogeneous damage database, collecting post-earthquake field surveys forms compiled in the aftermath of the 2009 L'Aquila seismic event. Field surveys were carried out on more than 73'000 buildings in the Abruzzi region, by using the first level form for post-earthquake damage assessment, short-term countermeasures and usability assessment of ordinary buildings (AeDES survey form, Baggio et al. 2007). Inspections were carried out on all residential buildings located in municipalities or hamlets with associated macroseismic intensity (MCS) higher than VI (Galli et al. 2009). In the other municipalities, buildings were surveyed if requested by the owners only (Dolce and Goretti 2015). Data corresponding to buildings located in the municipalities completely surveyed were thus identified, by selecting all sites with associated macroseismic intensity higher than VI, together with municipalities where at least 90% of buildings was inspected. The complete damage database hence reduced to about 51'000 survey forms, to be systematically classified into predefined building typologies and levels of damage, for a uniform interpretation of results. Additionally, data processing required the association of a ground motion intensity measure to each inspected building.

2.1 Seismic input characterization

Similarly to existing studies (e.g. Sabetta et al. 1998; Rossetto and Elnashai 2003; Del Gaudio et al. 2017), the peak ground acceleration (PGA) was selected as ground motion intensity measure and it was assumed to be constant (on average) at the municipality level (e.g. Rota et al. 2008). PGA was estimated on equivalent rock and for normal fault conditions via the ground motion prediction equation (GMPE) of Bindi et al. (2014a, b), developed for Europe and Middle East. The main characteristics of the L'Aquila mainshock were extrapolated from the RESORCE database (Akkar et al. 2014), for consistency with the selected ground motion prediction equation. Figure 1 (left) shows the PGA spatial distribution in the Abruzzi region. The right part of Figure 1 presents the subdivision of data into predefined PGA intervals. About 57% of the buildings falling in the PGA range 0.25-0.30g derives from constructions located in the L'Aquila municipality.

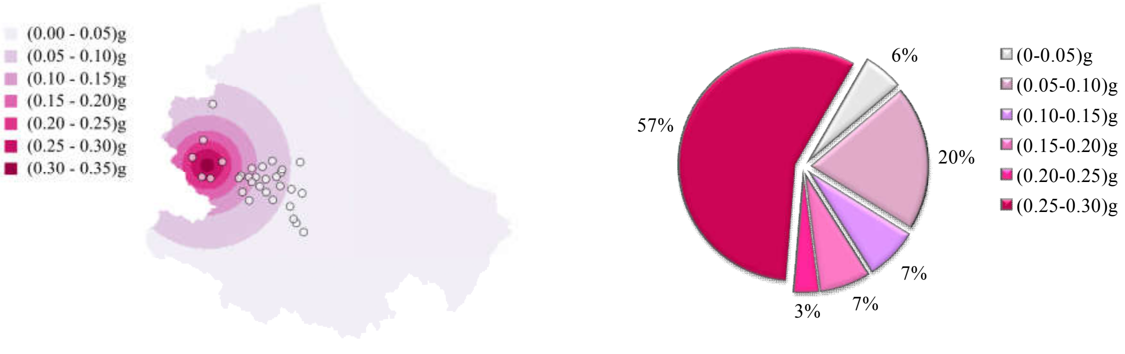

Figure 1. PGA spatial distribution in the Abruzzi region with indication of the selected municipalities (left) and subdivision of the data into different PGA intervals (right).

2.2 Identification of building typologies

Damage probability matrices are derived for building typologies, identified by collecting constructions with similar expected seismic behavior, according to a predefined taxonomy. Broad building classes could be easier to be defined and used. However, they may include buildings with different seismic performance, implying an average estimate of the seismic vulnerability, which may not be representative of any specific typology. From here, the need of addressing more refined typological classification systems.

To account for the heterogeneity of the exposed built environment, data were classified according to the RISK-UE (2004) typological classification system, suitably revised by Rota et al. (2008). Buildings were allocated into twenty-three typologies, firstly identified according to the type of the vertical bearing structure. For a detailed description of the selected building typologies, the reader is addressed to Rota et al. (2008). Data subdivision based on the construction material shows that masonry buildings represent 69% of the available dataset, reinforced concrete buildings 22%, mixed structures 8%, whereas steel buildings are only 1%. Figure 2 (left) shows the subdivision of buildings into six PGA intervals. It is observed that, in all cases, the majority of buildings is in the PGA bin 0.25-0.30g. On the right part of Figure 2, masonry buildings are subdivided based on masonry texture and quality (i.e. undressed and dressed stone) and presence of tie-rods and tie-beams. It is observed that undressed stone masonry buildings without connecting devices represent almost 50% of the available dataset of masonry constructions.

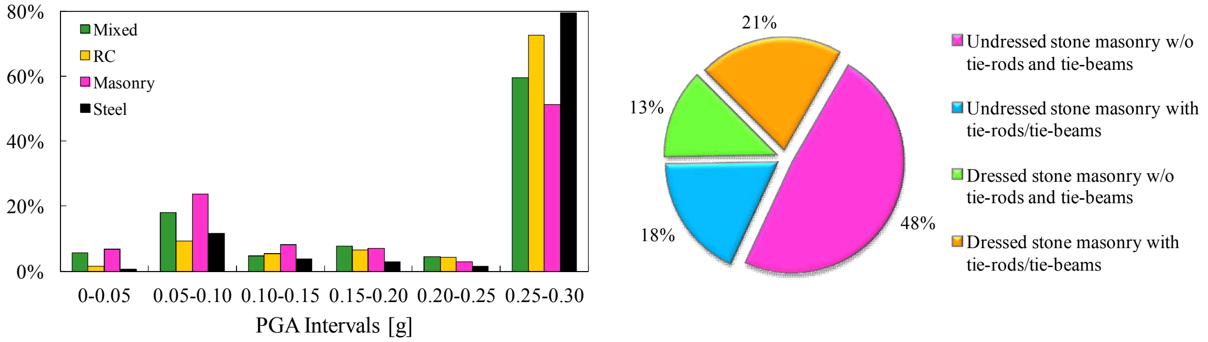

Figure 2. Distribution of buildings, classified according to the construction material, into PGA intervals (left) and statistics of masonry buildings (right) considering masonry layout and quality (i.e. undressed and dressed) and presence of connecting devices (i.e. tie-rods and tie-beams).

2.3 Observed seismic damage

Referring to the condensed damage levels of the EMS98 macroseismic intensity scale (Grünthal 1998), the AeDES damage classification considers both damage severity (i.e. D0: null damage; D1: slight damage; D2-D3: medium-severe damage and D4-D5: very heavy damage) and extent (i.e. <1/3; 1/3<e<2/3 and >2/3) on different building components (i.e. vertical structure, horizontal structure, stairs, roof, masonry infills and partitions). In Figure 3, the available damage data are subdivided based on the severity and extent of the observed damage on different building components. Similarly, Figure 4 depicts the damage repartition on different building components, conditioned on damage severity. The plot shows that the largest frequency of occurrence of D2-D3 and D4-D5 was detected on the vertical bearing structure.

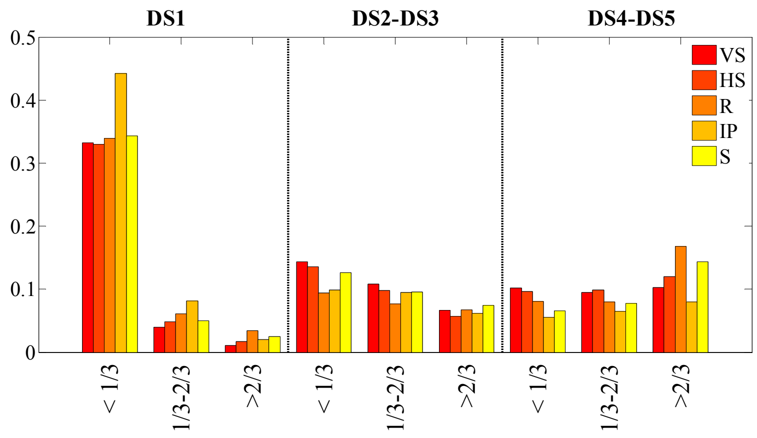

Figure 3. Severity and extent of damage observed on different building components. VS: vertical structure; HS: horizontal structure; R: roof; IP: masonry infills and partitions; S: stairs.

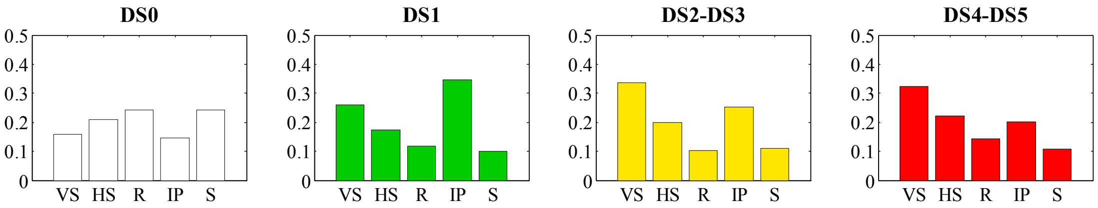

Figure 4. Observed frequency of the severity of damage on different building components. VS: vertical structure; HS: horizontal structure; R: roof; IP: masonry infills and partitions; S: stairs.

3. CLASSIFICATION OF THE OBSERVED DAMAGE

3.1 Existing approaches for the definition of damage states

The definition of damage levels is oriented to consistently assign each building a state of damage. Given the information on damage reported in the survey form, a suitable damage rule, converting damage descriptions of the survey form into discrete damage levels of a preselected damage scale, is needed. Once damage is evaluated individually on different building components, the overall building damage classification is then driven by the average or maximum damage value. The first category of approaches defines building global damage levels as the average damage weighted on preselected building components (e.g. Di Pasquale and Goretti 2001; Angeletti et al. 2002; Lagomarsino et al. 2015; Rosti et al. 2017). This requires a suitable weight classification system, taking into account the relative cost or importance that each component plays with respect to the whole structure. By contrast, the alternative class of approaches defines the overall damage based on the maximum observed damage, which mainly drives usability outcomes (e.g. Rota et al. 2008; Dolce and Goretti 2015; Del Gaudio et al. 2017; Rosti et al. 2017).

3.2 Comparison of different damage conversion rules for maximum damage-based approaches

Considering that the maximum observed damage on the most damaged component mainly impacts damage and usability assessment, damage probability matrices of predefined building typologies were derived by applying maximum damage-based approaches. Two damage conversion rules (Table 1) were selected to convert the information on damage reported in the survey form into discrete damage levels and assess their impact on resulting DPMs. Both damage conversion rules refer to damage states DS0 (null damage), DS1 (negligible to slight damage), DS2 (moderate damage), DS3 (substantial to heavy damage), DS4 (very heavy damage) and DS5 (collapse). The only difference between the two relations consists in the selection of the damage state corresponding to the damage description D1 with extent larger than 2/3.

Table 1. Selected damage conversion rules for maximum damage-based approaches

	Null	**D1**			**D2-D3**			**D4-D5**		
		e<1/3	1/3<e<2/3	e>2/3	e<1/3	1/3<e<2/3	e>2/3	e<1/3	1/3<e<2/3	e>2/3
Di Pasquale and Goretti (2001)	DS0	DS1	DS1	DS2	DS2	DS3	DS3	DS4	DS4	DS5
Rota et al. (2008)	DS0	DS1	DS1	DS1	DS2	DS3	DS3	DS4	DS4	DS5

Levels of damage were defined by considering both the aforementioned damage conversion rules and then taking the maximum among vertical bearing structure, horizontal structure and roof. Figure 5 shows results obtained for six PGA intervals and different building typologies. All the typologies include undressed stone masonry buildings with flexible horizontal structure and differ in the number of stories and presence of connecting devices (i.e. tie-rods and tie-beams).

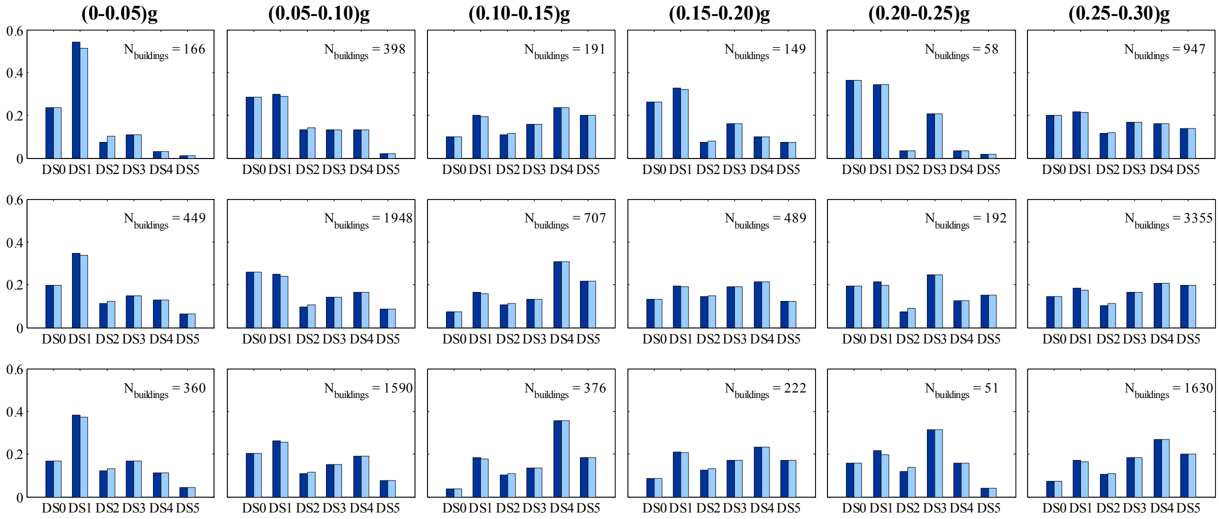

Figure 5. Comparison of empirical damage distributions resulting from different damage conversion rules: Rota et al. (2008) in blue and Di Pasquale and Goretti (2001) in light-blue. Undressed stone masonry with flexible horizontal structure and: with tie-rods/tie-beams and 1-2 stories – 1909 buildings (top); without tie-rods/tie-beams and 1-2 stories – 7140 buildings (centre) >2 stories – 4229 buildings (bottom).

The comparison of frequencies of occurrence of damage states DS1 and DS2, obtained from the two damage conversion rules, shows small differences. This finding is in line with Figure 3, where the frequency of occurrence of D1 with extent larger than 2/3 is considerably low with respect to the other cases. Therefore, moving data with D1 and e>2/3 from DS1 to DS2 may not significantly change the trend of the resulting damage distributions. In other words, data trend resulted to be insensitive to the damage definition of the adopted conversion rules.

4. APPROACHES TO ACCOUNT FOR A BIMODAL REPARTITION OF DAMAGE STATES

Empirical damage data are commonly represented in the form of histograms, which provide the frequency of occurrence of the different damage levels, for a given level of ground motion shaking. To make these distributions usable for other applications, histograms can be approximated by probability distributions. In this context, the binomial distribution has been extensively employed by past studies (e.g. Braga et al. 1982; Sabetta et al. 1998), mainly for its simplicity and easiness. Indeed, the binomial model is described by a single parameter, i.e. the mean damage, μ_D, of the discrete distribution. Assuming a binomial repartition of damage states, the number of buildings experiencing damage level DS_k can be expressed as:

$$N_k = N_{tot} \frac{n!}{k!(n-k)!} \left(\frac{\mu_D}{n}\right)^k \left(1 - \frac{\mu_D}{n}\right)^{n-k} \tag{1}$$

where N_k is the number of buildings undergoing damage level DS_k, N_{tot} is the total number of buildings in the considered ground motion intensity interval, n is the number of damage levels and $k = 0 \div n$.
The mean damage of the discrete distribution is then given by:

$$\mu_D = \sum_{k=0}^{n} \frac{N_k}{N_{tot}} k \tag{2}$$

In accordance with existing studies, the binomial distribution was selected to approximate observed frequencies of occurrence of the different damage states. In the following, results are shown for low-rise buildings with undressed stone masonry, flexible horizontal structure and without tie-rods and tie-beams, which is selected as a case study. For the selected typology, Figure 6 shows the binomial approximation (light grey bars) of observed damage distributions (dark grey bars). It can be noted that the binomial model does not satisfactorily approximate all levels of damage. Indeed, the binomial distribution captures the trend of data with low damage in some PGA intervals (e.g. in the PGA range 0-0.05g and 0.05-0.10g), but it does not allow to predict higher damage states. Differently, in other PGA intervals, the binomial model better describes the trend of higher damage levels, without providing satisfying estimates of lower damage states.
The limitations of the classical binomial model to reproduce the observed damage subdivision in the different states is ascribed to the peculiar trend of the empirical data, which seem to follow two distinct distributions, one for DS0 and DS1 and the other one for damage levels from DS2 to DS5. This bimodal trend of damage repartition also exhibits a high probability of occurrence of slight damage, with respect to the other states.

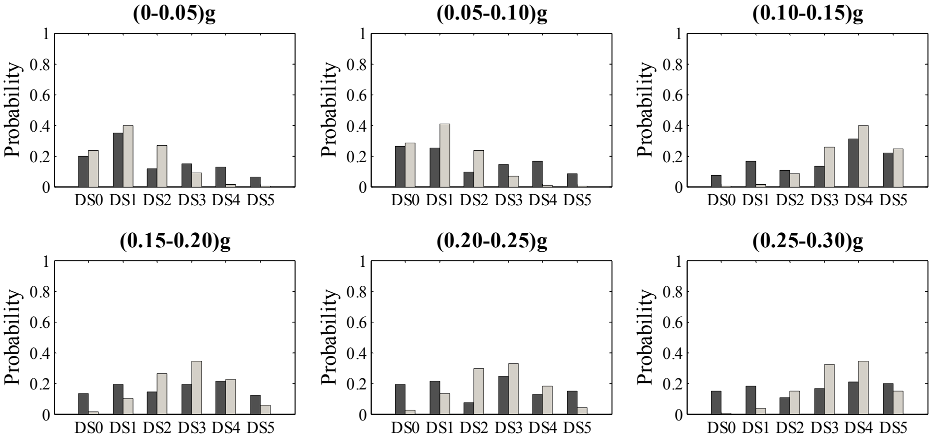

Figure 6. Comparison of empirical DPMs (dark grey bars) with binomial prediction (light grey bars), for low-rise buildings with undressed stone masonry, flexible horizontal structure and without tie-rods and tie-beams (7140 buildings).

As pointed out by Rossetto et al. (2013), these trends could be due to misclassification errors or to unskilled inspectors with issues when evaluating lower damage levels. At lower values of the ground motion shaking, the high probability of occurrence of DS1 could be also explained by pre-existing damage, that is damage presumably existing before the earthquake, often driven by bad preservation or even by lack of maintenance conditions. The bimodal trend of damage repartition may be also driven by the presence, within the same structural typology, of buildings of different vulnerability. Although a refined typological classification system was adopted to group buildings with similar seismic performance, buildings' heterogeneity may be entailed by some vulnerability parameters and structural configurations which are not contemplated by the adopted taxonomy (e.g. plan and elevation irregularities) or by the survey form (e.g. walls and openings distribution, construction details, architectural configuration), but which may impact the buildings' seismic response. Additional sources of uncertainty may concern the seismic input characterization, such as the use of a GMPE to estimate the ground motion severity, the definition of isoseismic units at the municipality level, the poor correlation between the observed seismic damage and the selected ground motion intensity measure. On the other side, the non-negligible frequencies of occurrence of DS5 at lower ground motion intensity levels can be explained by the presence of intrinsically vulnerable buildings, even prone to collapse before the occurrence of the seismic event. This observation is in line with observations by Galli et al. (2009).

A first hybrid procedure was hence developed to interpret and account for the bimodal repartition of damage in the different states. The binomial model was imposed on buildings experiencing damage levels higher than DS1, thus excluding data with DS0 and DS1 from the fitting. The unknowns of the problem, obtained by the combined use of Equations (1) and (2), are thus the mean damage of the discrete distribution and the number of buildings binomially distributed, which in this case is not equal to the total number of buildings in the ground motion intensity level under investigation. Optimal values of the unknowns were derived by minimizing the sum of the squared errors between predictions and observations. The optimization problem was solved by imposing the equality between the observed and predicted number of buildings undergoing damage levels from DS2 to DS5. This constraint allowed to detect the number of constructions with damage levels DS0 and DS1, escaping the imposed binomial model. As an example, Figure 7 shows the implementation of the procedure for two PGA intervals, with reference to the selected building typology.

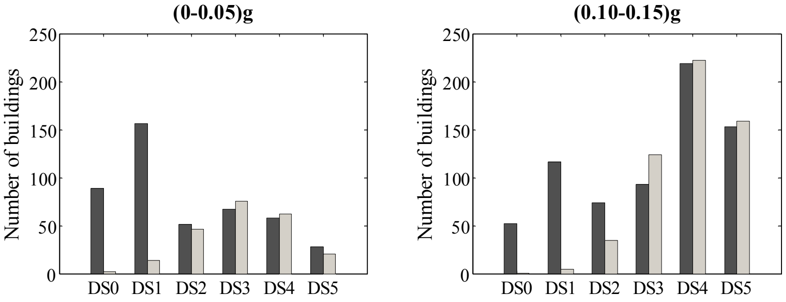

Figure 7. Comparison of the observed (dark grey) and predicted (light grey) number of buildings, according to the first hybrid procedure, for low-rise undressed stone masonry buildings with flexible horizontal structure and without tie-rods and tie-beams.

For a given ground motion intensity level, the implementation of the procedure allows to identify the fraction of buildings binomially distributed and the percentage of buildings which instead deviate from the imposed binomial model. By applying this approach to all the predefined ground motion intensity levels, the trend of the fraction of constructions escaping the imposed binomial model can be derived as a function of the preselected ground motion intensity measure (Figure 8, left). A logarithmic regression line was then used to fit the trend of data, y, as a function of PGA:

$$y = a_1 \ln(\mathrm{PGA}) + a_2 \tag{3}$$

where, for this specific case study, the regression coefficients a_1 and a_2 turned out to be equal to -0.09 and 0.18.

Figure 8 (centre) shows the repartition of buildings binomially distributed, as a function of PGA. In accordance with existing studies (e.g. Lagomarsino and Giovinazzi 2006; Rota and Rosti 2017; Rosti and Rota 2017) the mean damage (μ_D) of the discrete distribution was selected as vulnerability indicator, representative of the overall damage distribution. The trend of the mean damage values was approximated by a logarithmic regression line to get a continuous description of the seismic vulnerability as a function of the seismic input:

$$\mu_D = b_1 \ln(\mathrm{PGA}) + b_2 \tag{4}$$

where b_1 and b_2 are equal to 0.19 and 3.89, respectively.

Thanks to the availability of continuous relations (Equations 3 and 4), hybrid damage distributions were punctually derived as a function of PGA. Figure 8 (right) shows the probability of occurrence of the different damage states, cumulated from the lowest to the highest level of damage, as a function of PGA. It is observed that buildings with null (DS0) or slight (DS1) damage are not marked, since the method does not allow to get indications on the actual percentages of buildings experiencing DS0 and DS1.

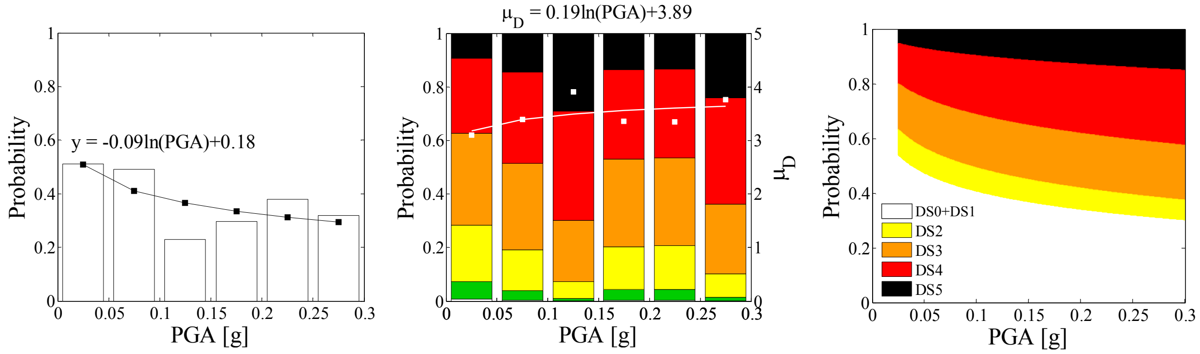

Figure 8. Fraction of buildings escaping the binomial model as a function of PGA (left); damage repartition of binomially-distributed buildings (centre); hybrid damage distributions as a function of PGA (right)

To counteract this limitation, an additional hybrid procedure was developed. This second approach makes use of two binomial models which are simultaneously imposed on the empirical damage data. The first binomial distribution better describes the repartition of constructions with damage levels DS0 and DS1, whereas the second model tends to capture the distribution of higher damage states. For a given damage state, the predicted number of buildings is thus given by the sum of the number of buildings predicted by each binomial model. For each distribution, the unknowns are the mean damage, μ_D, and the number of buildings following the distribution. Optimal values of the unknowns are derived by minimizing the sum of the squared errors between predictions and observations, under the constraint for which the sum of the number of buildings following the two binomial distributions must be equal to the total number of constructions in the ground motion intensity level under consideration. The implementation of the procedure is shown in Figure 9, comparing the empirical DPMs with predictions, for two PGA intervals (i.e. 0-0.05g and 0.10-0.15g). Predictions are differentiated based on the contribution provided by each binomial model. In particular, white bars refer to the first binomial distribution, better describing the trend of lower damage levels, whereas pink denotes the second binomial model, which instead mainly captures the repartition of higher damage states. The sum of the contributions of the two binomial distributions provides the overall prediction. In the figure, the number of buildings in the PGA interval and the mean damage values of each binomial distribution are also indicated. Differently from the previous hybrid procedure, this approach provides estimates of the frequency of occurrence of all damage levels.

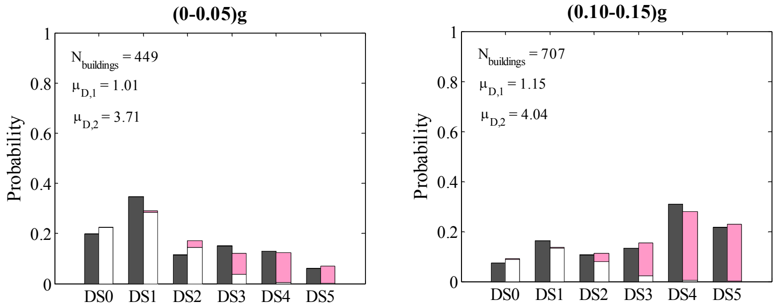

Figure 9. Comparison of empirical damage distributions (dark grey bars) with predictions, distinguished based on the contribution provided by the first (white bars) and second (pink bars) binomial distribution.

For each ground motion intensity level, the method provides the fraction of buildings following the first and second binomial distributions, respectively, and the mean damage value of each distribution. Figure 10 (left) shows the percentage of buildings following the first (white bars) and second (pink bars) binomial distribution, as a function of PGA. The trend of buildings following the first binomial distribution was approximated by a logarithmic regression line. Figure 10 (centre) depicts the mean damage values of each binomial distribution for different ground motion intensity levels. It is interesting to note that the μ_D values of each distribution tend to oscillate around a constant value. The trend of μ_D as a function of PGA was thus approximated by a constant regression line and the difference in the resulting hybrid damage distributions is given by the fraction of buildings following the first binomial distribution, which decreases with the ground motion severity. The use of regression lines in different steps of the outlined procedure allowed to get continuous hybrid damage distributions as a function of PGA (Figure 10, right). Similarly to Figure 8 (right), probabilities of occurrence are cumulated from the lowest to the highest level of damage.

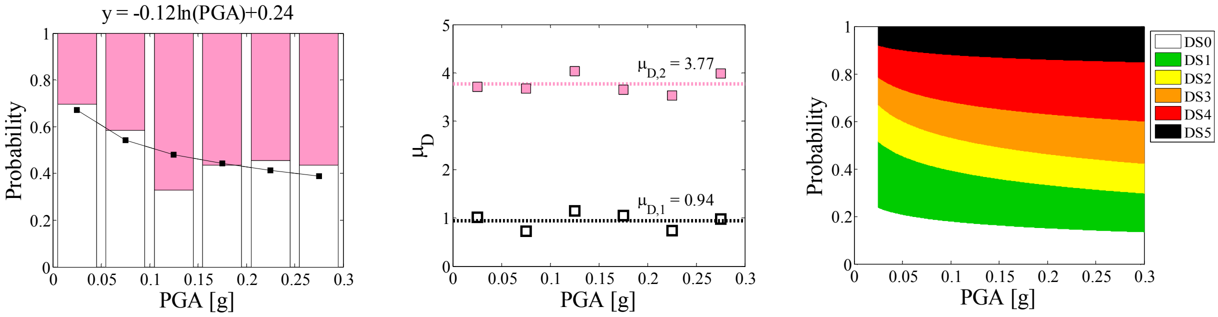

Figure 10. Fraction of buildings following the first (white bars) and second (pink bars) binomial distribution, as a function of PGA; horizontal regression lines of the mean damage values defining the first (white markers) and second (pink markers) binomial distribution (centre); hybrid damage distributions as a function of PGA, resulting from the implementation of the second procedure (right).

Figure 11 plots empirical damage data (round markers) against predictions, derived from the implementation of both hybrid procedures. The main difference between the two approaches is in the estimation of the probability of occurrence of DS1, given that the first procedure does not permit to get the fractions of buildings undergoing DS0 and DS1, respectively. As already discussed, this limitation is intrinsic in the method. For the other damage states, the trend of predictions is similar, although some differences can be visually observed (e.g. the probability of occurrence of DS2 is larger when predicted by the second approach). These comparisons are however qualitative and suggest a deeper and quantitative investigation of the accuracy of the methods to approximate observed damage data. More details on the proposed procedures can be found in Rosti et al. (2017).

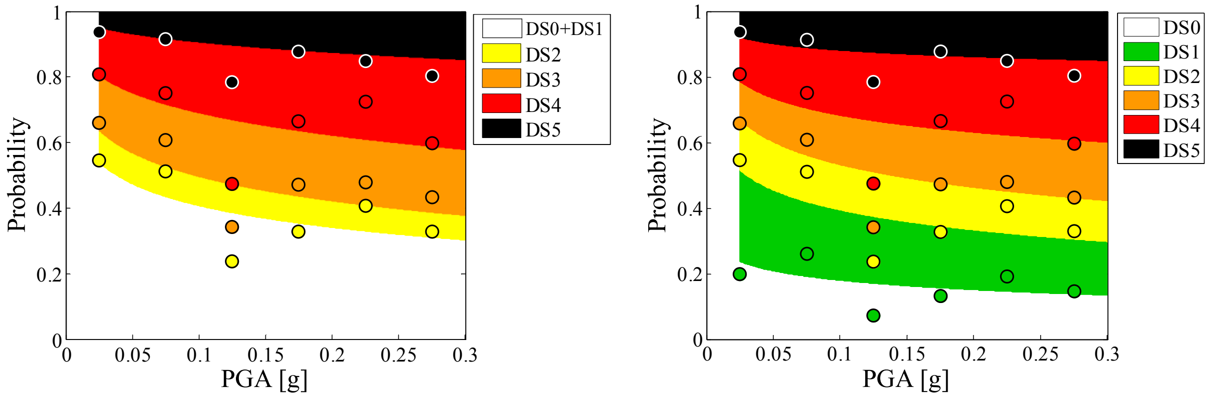

Figure 11. Comparison of empirical damage data (round markers) with predictions derived from the implementation of the first (left) and second (right) hybrid procedure.

5. CONCLUSIONS

This paper explores the effect of different damage definitions on the empirical seismic vulnerability of building typologies representative of the Italian building stock, by taking advantage of a complete and homogeneous damage database. Different damage classifications and approaches, commonly adopted in the literature to assign each inspected building a univocal global damage level, are examined and their impact on empirical damage probability matrices is assessed. DPMs of several building typologies exhibited a bimodal tendency of damage to distribute in the different states, which resulted to be insensitive to the adopted damage classifications. Empirical damage distributions also showed a considerable frequency of occurrence of slight damage, with respect to the other levels. Uncertainties related with the acquired data and pre-existing damage, typically characterizing old and highly vulnerable masonry buildings, are some of the several interpretations that can explain this outcome.

Empirical DPMs are first approximated by imposing the binomial distribution, which does not provide satisfactory results, given the singular trend of the same empirical damage data. Two hybrid approaches are thus proposed to interpret and account for the bimodal repartition of damage in the different states. Both the methods make use of the binomial model to approximate the observed frequencies of occurrence of the different damage levels and lead to continuous hybrid damage distributions as a function of the selected intensity measure. The feasibility of each procedure is illustrated with reference to a case study. Although straightforward, the first method, imposing the binomial distribution on buildings with damage levels from DS2 to DS5, does not permit to distinguish the proportion of buildings with null and slight damage. By contrast, the second procedure simultaneously imposes two binomial distributions on empirical damage data and allows to capture the whole bimodal repartition of damage in the different states.

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