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TYPOLOGICAL SEISMIC LOSSES ASSESSMENT BY DAMAGED MASONRY BUILDINGS AFTER L'AQUILA 2009 AND EMILIA 2012 EARTHQUAKES

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Abstract

In this paper a seismic risk analysis of masonry buildings based on damage data from the 2009 L'Aquila and 2012 Emilia earthquakes. The seismic vulnerability is described by fragility curves from which economic loss curves are derived for each representative typological class of masonry buildings. The information on the buildings was collected by the Italian Civil Protection Department with the AeDES form and available in the Observed Damage Database (D.a.D.O.). The reliability of the database considered, however, was improved by carrying out a process of estimating undamaged buildings from data from the 15th ISTAT census. Finally, for each damage level, according to EMS-98 scale, a procedure to derive the Expected Annual Loss is presented, so as to express its percentage contribution in the seismic risk assessment.

Keywords: damage observed, empirical fragility curves, masonry buildings, seismic risk, expected annual loss.

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1 INTRODUCTION

The earthquakes cost that have affected the Italian territory since the Belice Valley 1968 seismic event has been actualized to 2014 as 121 billion euros ([1]), aggravated by the presence of more than 4,000 casualties. What has happened has revealed the high fragility of Italy's building stock, highlighting the need to act preventively with safety controls, especially in high-risk areas. In particular, recent studies have highlighted as certain structural elements, which undergoing seismic action, influence the vulnerability of masonry ([2]) and R.C. ([3]) buildings. Therefore, the economic resources scarcity to upgrade the building stock on the part of administrations, there is an increasing need to develop legislative and methodological tools able to guide economic resources for optimal mitigation of seismic risk on a large scale. For this reason, the study of past events is a powerful way to lead to the definition of tools to derive the seismic vulnerability of existing buildings quickly.

Within this framework, a pioneering study in Europe is found in [4], where about 36000 buildings were analyzed after the Irpinia 1980 earthquake for deriving Damage Probability Matrices (DPMs). More recently, for instance are the work of [5], [6], [7] where fragility curves were proposed by using the damage registered after the L'Aquila 2009 earthquake, while in [8], [9] the seismic damage registered after Emilia 2012 was considered. In addition, recently seismic risk analysis was conducted by L'Aquila 2009 earthquake in [10], [11], while in [12] also Emilia 2012 earthquake are considering.

In this study a seismic risk analysis is presented, starting from the derivation of typological economic loss curves for residential masonry buildings. In particular, is carrying out a comparison among the results obtained from damage observed data on masonry buildings stocks after the L'Aquila 2009 and Emilia 2012 earthquakes. The buildings stocks consider are available in the Da.D.O. (Observed Damage Database) web-gis database ([13], [14]) where several information are collected from AeDES forms ([15]) for 74,049 and 22,554 buildings hit by the L'Aquila 2009 and Emilia 2012 earthquakes.

Therefore, a comparison of typological economic losses for the residential masonry buildings is conduct in this work, and are shown the specifically economic losses, expressed through the Expected Annual Loss (EAL) ([16], [17]), for the epicentral municipality of L'Aquila and Mirandola. Finally, by applying the presented method are shown the contribution of each damage level in the seismic risk assessment.

2 L'AQUILA 2009 AND EMILIA 2012 BUILDING STOCKS

2.1 Statistical analysis on surveyed buildings

L'Aquila 2009 and Emilia 2012 earthquakes had a destructive impact on the corresponding epicentral areas, with a macro-seismic intensity of I_{MCS} = IX-X and I_{MCS} = VIII respectively ([18]). Consequently to the respectively mainshock, a survey activity was conducted on the buildings affected by the earthquakes to verify the damage suffered and the serviceability of ordinary buildings using the AeDES form [15].

AeDES form information for L'Aquila 2009 and Emilia 2012 earthquakes related to 74,049 and 22,554 buildings, respectively, in 129 and 55 municipalities, are available in the DaDO database ([13], [14]), where collects the data of ordinary buildings surveyed after the principal Italian seismic events (Friuli 1976, Irpinia 1980, Abruzzo 1984, Umbria-Marche 1997, Pollino 1998, Molise e Puglia 2002, Emilia 2003, L'Aquila 2009, Emilia 2012, Garfagnana-Lunigiana 2013 and Mugello 2019). More in detail, only residential buildings are considered in this work, where in the L'Aquila 2009 and Emilia 2012 stocks consists in 68,556 (n. 95 municipalities) and 17,301 (n. 45 municipalities) AeDES forms respectively.

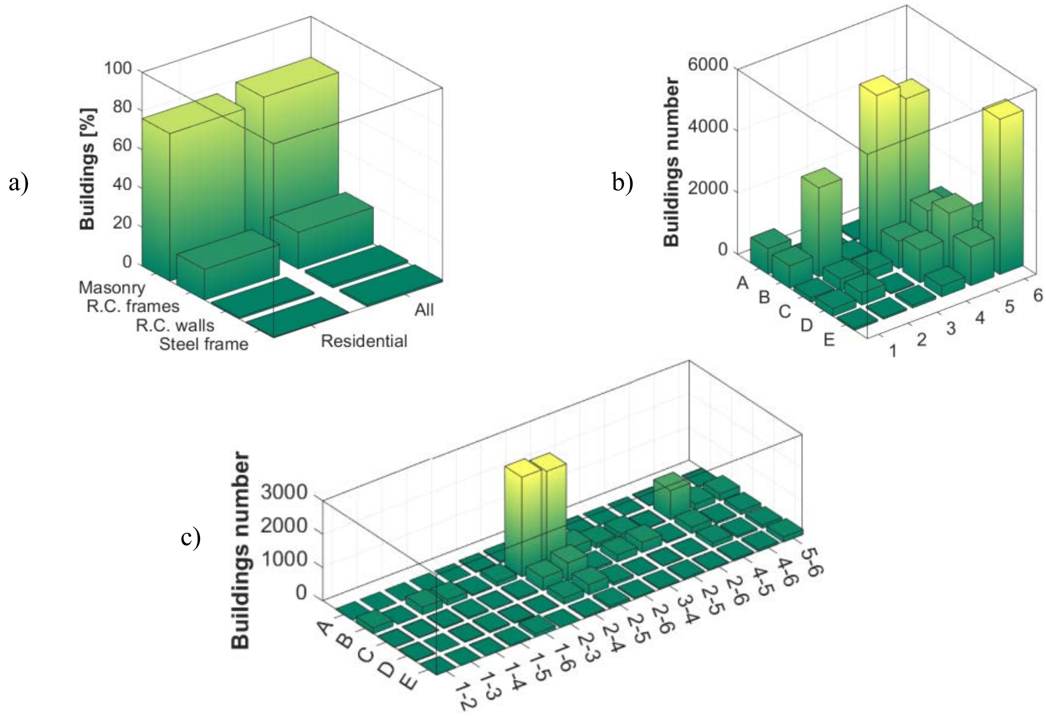

Figure 1: Distribution of building stock surveyed after L'Aquila 2009 earthquake: a) all and residential structural for material typologies surveyed; b) masonry buildings with a combination of one vertical structure and one horizontal structure; c) masonry buildings with a combination of one vertical structure and two horizontal structures.

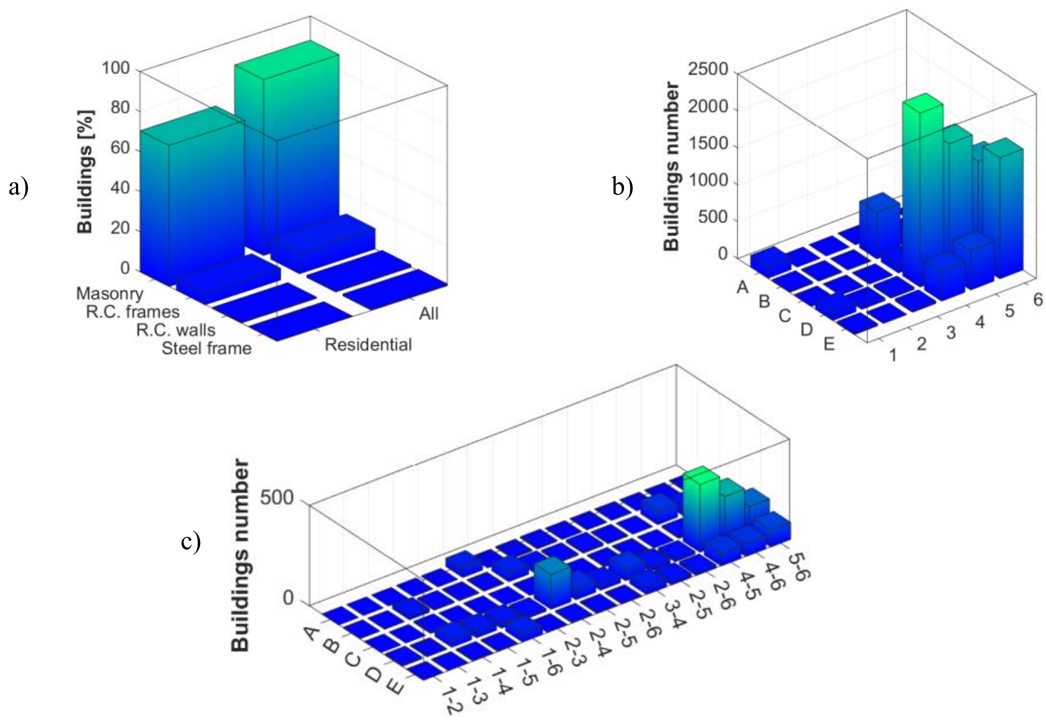

Figure 2: Distribution of building stock surveyed after Emilia 2012 earthquake: a) all and residential structural for material typologies surveyed; b) masonry buildings with a combination of one vertical structure and one horizontal structure; c) masonry buildings with a combination of one vertical structure and two horizontal structures.

Figure 1 and Figure 2 depicts the percentage distribution of typologies surveyed for both earthquakes considered. In particular, Figure 1a and Figure 2a highlight, with a 3D- histogram, the percentage of buildings residential respect all building surveyed for each typology in terms of construction material (masonry, R.C. frames, R.C. walls and steel frames). Is clear to observe that the dominant typology is represented by masonry structures where it has a recurrence of 79% (76% residential) and 88% (71% residential) in the buildings surveyed after L'Aquila 2009 and Emilia 2012 earthquake respectively. R.C. frame structure is less frequent, with 19% (16% residential) for L'Aquila 2009 and 10% (6% residential) for Emilia 2012, such as R.C. walls and steel frames structures (about less 1%).

The sample analyzed in this study consists only in masonry buildings with 56,338 and 15,903 AeDES forms related to L'Aquila 2009 and Emilia 2012 earthquake having the typological classes distribution indicated in Figure 1b, Figure 1c (L'Aquila 2009 stock) and Figure 2b, Figure 2c (Emilia 2012 stock), and described in Table 1 [15].

Masonry Buildings		N.I. (A)	Poor quality w/ chains (B)	Poor quality w/o chains (C)	Good quality w/ chains (D)	Good quality w/o chains (E)
N.I.	(1)	1A	1B	1C	1D	1E
Vaults w/o chains	(2)	2A	2B	2C	2D	2E
Vaults w/ chains	(3)	3A	3B	3C	3D	3E
Beam w/ deform. slabs	(4)	4A	4B	4C	4D	4E
Beam w/ semi-rigid slabs	(5)	5A	5B	5C	5D	5E
Beam w/ rigid slabs	(6)	6A	6B	6C	6D	6E

Table 1: Typological classes for masonry buildings according to the AeDES form

In Figure 1b and Figure 2b depicts the distribution of masonry buildings having a combination with one type of vertical and horizontal structure for L'Aquila 2009 and Emilia 2012 stocks, corresponding to 56% and 61% respectively. Note that among the typologies, thus defined, the more typologies observed to L'Aquila 2009, showed in Figure 1b, are 2B (n. 2,895 buildings), 4B (n. 5,172 buildings), 5B (n. 4,700 buildings) and 6E (n. 5,045 buildings), while in Emilia 2012 stock (Figure 2b) are 4D (n. 2,357 buildings), 5D (n. 1,790 buildings), 6D (n. 1,400 buildings) and 6E (n. 1,639 buildings). Furthermore, Figure 1c and Figure 2c shown the distribution of masonry buildings with a combination of two horizontal structures and one vertical structure (28% and 15% respectively in L'Aquila 2009 and Emilia 2012 stocks).

2.2 Global damage assessment

Observed damage after the seismic sequence of L'Aquila 2009 and Emilia 2012 is classified according to four damage intervals, such as D_0 (null damage), D_1 (low damage), D_2-D_3 (moderate or heavy damage) and D_4-D_5 (very heavy damage or collapse) present in AeDES forms. These, they are assigned to each structural element of the buildings surveyed (: vertical structures, floors, stairs, roofs, partitions, and pre-existing damage before the seismic event occurred) and are shown in Figure 3. It is clear to observed that for each damage distribution, among the different structural elements, the vertical elements result always the most damaged, except to D_1 in Emilia 2012 stock where partitions are greater. However, order to assign a global damage starting from the damage classification with AeDES form, the first step is defined a unique damage level for each structural element in according to EMS-98 scale [19] , such as defined in ([13], [14]).

In this study, the global damage is assigned following the maximum damage observed among the building components (i.e., vertical structures, floors, and roofs) according to the work of [20]. Furthermore, the choice to consider the maximum damage was chosen in relation to the dependence of the usability of the structure and the related repair costs ([10]).

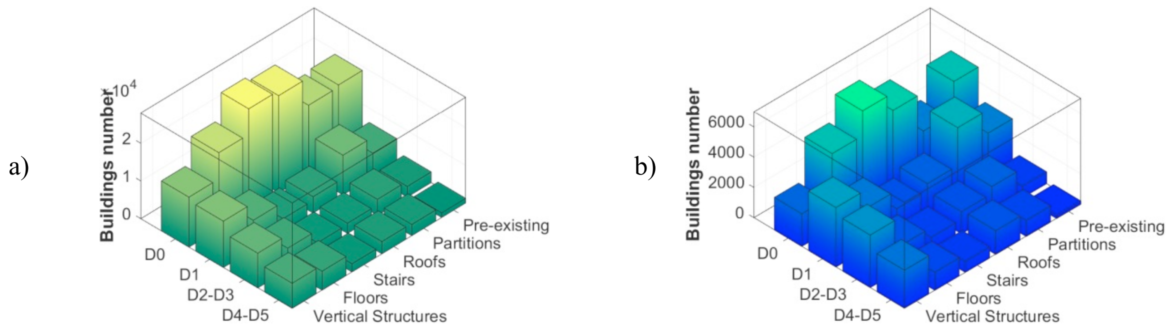

Figure 3: Damage distribution for different structural elements of residential masonry buildings: a) L'Aquila 2009 earthquake; Emilia 2012 earthquake

2.3 Estimate of unsurveyed buildings

In order to perform a more reliable analysis of the observed seismic damage within the considered buildings stocks, it is reasonable to understand whether the AeDES forms collected within the Da.D.O. database represent all the buildings that suffered the L'Aquila 2009 and Emilia 2012 earthquakes.

First, an analysis on the state of completeness must be performed, which is carrying out by taking 15th census recorded by the Italian National Statistics Institute (ISTAT, [21]) in 2011 as the reference database. In particular, municipality-by-municipality the following Completeness Ratio (r_m) may be considered ([10], [11]):

$$r_m = \frac{N_{m,AeDES}}{N_{m,ISTAT}} \quad (1)$$

where m are the municipalities for L'Aquila 2009 (from 1 to 95) and Emilia 2012 (from 1 to 45); $N_{m,AeDES}$ is the buildings number surveyed within Da.D.O. database, while $N_{m,ISTAT}$ is the buildings number in the 15th census of ISTAT 2011.

Figure 4 shows the completeness ratio distribution within of five r_m intervals ($r_m \geq 1$; $1 < r_m \leq 0.8$; $0.8 < r_m \leq 0.5$; $0.5 < r_m \leq 0.1$; $r_m < 0.1$). Specifically, a double vertical axis indicating the municipalities numbers (on the left) and the related percentage (on the right) shown with larger (buildings numbers) and inner tighter histograms (buildings percentage), and a dashed line representing the cumulative distribution percentage.

In Figure 4a it is clear to observe that, in after L'Aquila 2009 earthquake, about 18% of the municipalities survey is completed, while in Emilia 2012 stock (Figure 4b) nothing municipalities result fully surveyed.

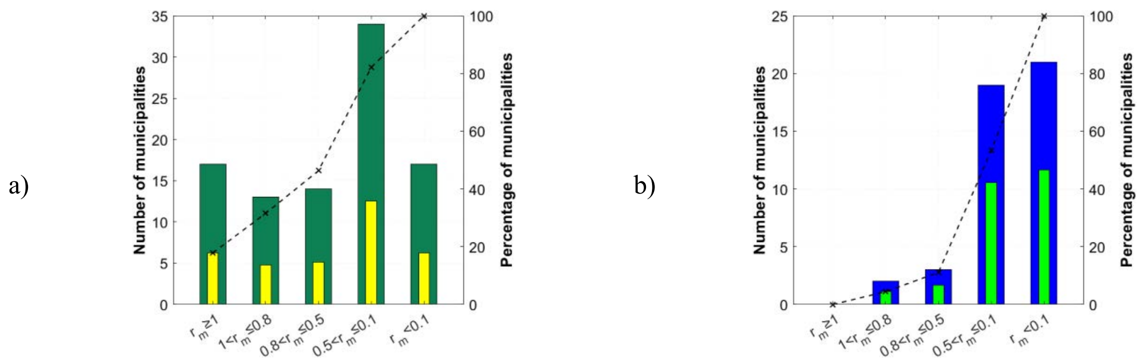

Figure 4: Distribution of Completeness Ratio r_m for different completeness thresholds: a) L'Aquila 2009 earthquake; b) Emilia 2012 earthquake

Therefore, there are residential buildings that have not been surveyed and have been undergone to the seismic sequence without suffering structural damage. Then, a procedure for completing the unsurveyed buildings is necessary.

In recent years, several completeness procedures are performed for improvement the available database. In [10],[22] and [11] it is proposed to evaluate the buildings typological distribution by referring to a completely surveyed municipality, while in [7], the database completion is performed considering a completeness index evaluated as a function of the PGA.

In this study, the proposed approach is to calculate municipality-by-municipality the number of undamaged buildings by comparing the number of survey buildings available in the Da.D.O. database with those in the ISTAT 2011 census ([12]). Furthermore, they are distributed into the various typologies of the buildings stock analysed by assuming that undamaged buildings are divide according to the percentage of surveyed buildings with damage D_0 available with AeDES form.

By applying the approach proposed the added number of undamaged masonry buildings is in total of n. 21,955 buildings for L'Aquila 2009 and of n. 76,643 for the Emilia 2012 building stock. Finally, the completed stock is composed by n. 78,293 and n. 92,546 residential masonry buildings for L'Aquila 2009 and Emilia 2012, respectively. In this way, masonry building database is completed and a seismic risk analysis is conducted in the next sections.

3 TYPOLOGICAL ECONOMIC LOSS ANALYSIS

3.1 Vulnerability classes

Seismic vulnerability analysis for residential masonry buildings is conducted by referring to three different classes with decreasing levels of vulnerability. as definitely in Da.D.O. database. These classes are named as *Class A* (high vulnerability), *Class B* (medium vulnerability) and *Class C1* (low vulnerability).

Specifically, with reference to Table 1, the vulnerability classes are defined by considering masonry with vertical structures, with the presence (or absence) of steel ring chains/beams at floor level, such as masonry of poor quality (*type B*, *C*) and good quality (*type D*, *E*), combined with horizontal structures, classified as vaults with/without chains (*type 2*, *3*, respectively), or deformable, semi-rigid or rigid floors with respect to the horizontal seismic action (*type 4*, *5*, *6*, respectively).

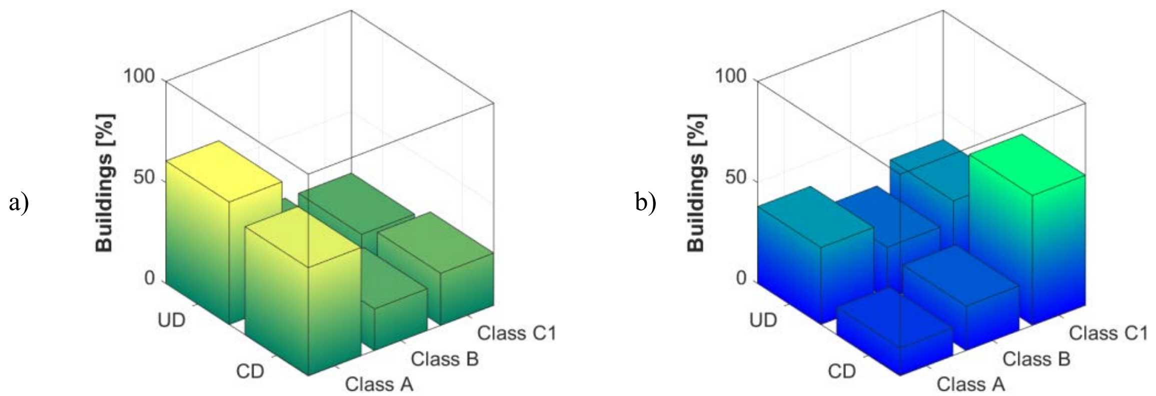

Figure 5: Breakdown of vulnerability classes *A*, *B* and *C1* for residential masonry buildings considering an uncomplete (UC) and complete database (CD) from L'Aquila 2009 (a) and Emilia 2012 (b) stocks

Figure 5 reports the percentage repartition for the two buildings stocks considered with reference to a uncomplete and complete database. It is noted that, with a uncomplete database (UD), in Emilia 2012 stock (Figure 5b) have a more regular buildings distribution among the three classes with respect to the L'Aquila 2009 stock (Figure 5a), where the *Class A* results about 60%. Instead, the completion criterion proposed in Sect. 2.3, leads to a more even distribution of vulnerability classes within the L'Aquila 2009 stock, while a greater preponderance of *Class C1* is observed in Emilia 2012 stock. However, it is due to the completion criterion's assumption, where presumably the most vulnerable buildings are fewer in number among the undamaged buildings than the least vulnerable.

3.2 Typological economic loss curves

Starting from the observed damage data available among the several seismic events into the Da.D.O. database, once the fragility curves have been derived on empirical based, it is possible quantifying the potential losses in economic terms for the residential masonry buildings. In particular, the typological economic loss curves are defined with reference to economic consequences express in terms of percentage of Reconstruction Cost (*%RC*) in accordance with [23].

First, an empirical fragility curve represents a continuous relation that expressed the conditional probability of having a damage level D equal to or greater than a given damage level D_i, for a predetermined Intensity Measures (IM) value. It is expressed through a log-normal cumulative distribution function, see (2):

$$P_{D\geq D_i} = \Phi\left(\frac{\ln\left(\frac{IM}{\vartheta}\right)}{\beta}\right) \quad i = 0, \dots, 5 \tag{2}$$

where $P_{D\geq Di}$ is the fragility function for the *i-th* damage conditioned to an intensity measure. Φ is the standard normal cumulative distribution function, θ and β are respectively the median value and the standard deviation of the logarithm of IMs.

The parameters (θ, β) are estimated by maximizing the product of the likelihood functions express with binomial probability distribution, such as proposed in [24]. In logarithmic form result

$$\left(\hat{\vartheta}_1, \hat{\vartheta}_2, \hat{\vartheta}_3, \hat{\vartheta}_4, \hat{\vartheta}_5, \hat{\beta}\right) = arg\,max\left\{\left[ln \prod_{i=1}^{5}\prod_{j=1}^{m}\binom{k_j}{z_j} P_{D\geq D_i}^{k_j}\left(1 - P_{D\geq D_i}\right)^{z_j - k_j}\right]\right\} \tag{3}$$

where the median value and the standard deviation of the logarithmic IM values for the fragility curves are obtained. k_j is the buildings number having a damage greater or equal than a *i-th* damage level, while z_j is the buildings number in the *j-th* sub-sample. It should be noted that to prevent the fragility curves crossing is considered a common value of standard deviation of the logarithmic IM values of for all the fragility curves [16].

In order to derive the typological economic loss curves, the next step consist to determine the damage probability curves as the difference between the exceedance probability curves (i.e., fragility curves). Now, for each damage level of the damage probability curves $P(D = D_i|IM)$, an economic consequence as a percentage of Reconstruction Cost (*%RC*) is assigned and then the typological economic loss curves can be defined for each damage level.

Finally, the global curve of the typological economic loss curves may be defined through the sum of the partial curves (i.e., typological loss curves of each damage level D_i), expressed as follows.

$$L_{tot}(IM) = \sum_{i=0}^{5} \%RC_i \cdot P(D = D_i|IM) \quad i = 0, \dots, 5 \tag{4}$$

where $\%RC_i$ is the percentage of Reconstruction Cost for *i-th* damage level; $P(D = D_i|IM)$ is the damage probability curve for *i-th* damage level.

Figure 6 shows, for residential masonry buildings, the total typological economic loss curves derived from the buildings stocks investigated after L'Aquila 2009 and Emilia 2012 earthquakes, where are indicate, respectively, with a green and blue line. In particular, with refer to the residential masonry building of vulnerability class *A*, *B* and *C1* in the building stocks analysed (L'Aquila 2009 and Emilia 2012 buildings stocks), dashed line in Figure 6 consider an uncompleted database (UD), while a solid line is depicts a complete database (CD).

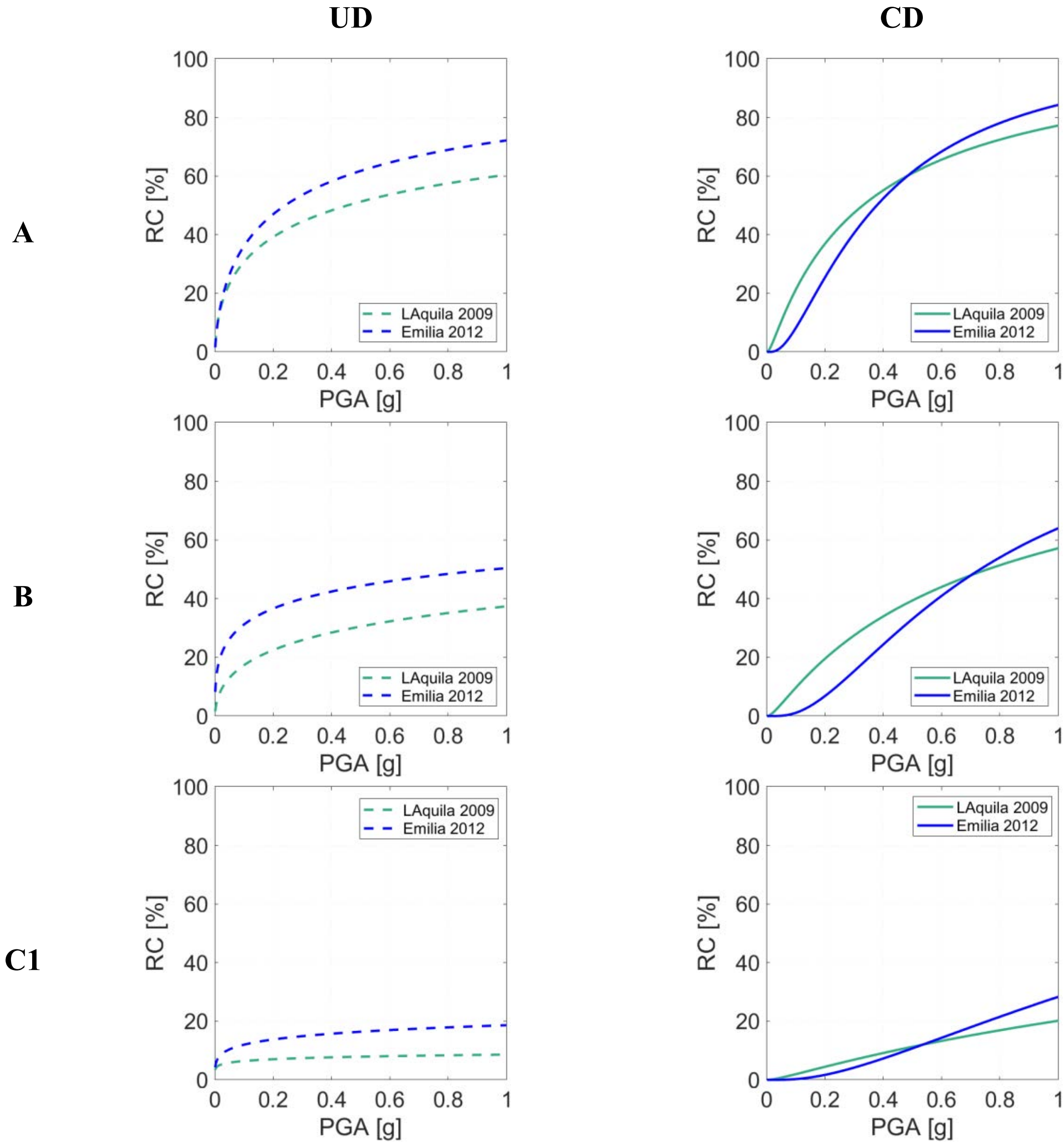

Figure 6: Comparison between typological economic loss curves for residential masonry buildings from L'Aquila 2009 and Emilia 2012

First, it can be observed that *Class A* with both database (uncompleted and completed database) confirms be the building typology with the higher vulnerability among the three class considered, where for a specific event, expressed with *PGA*, it has a higher percentage of reconstruction cost (*%RC*). Furthermore, is clear the influence of the completion database, where the curves in Figure 6 result significantly different and the adoption of adequate criterion for estimate the buildings stock not surveyed is central in a correct evaluation of economic losses. In addition, it should be noted that although building classes defined with the same selection criteria were considered in the different databases analyzed, the typological economic loss curves, observed in Figure 6, do not show a clear correlation. However, this would have to be investigated in detail but, in any case, it could probably be due to the fact that are presents most different typologies within the vulnerability classes. In fact, as seen in Sect. 2.1, the breakdown of typological classes according to AeDES form is particulary different in the building stocks, highlighting the use of different building characteristics, specific to a geographic area. This means that vulnerability classes are too wide to summarize, indipendently from the buildings stocks, the structural behaviour of a group of buildings. Therefore, one should refer to multiple seismic events to better accounting for the uncertainties in macroseismic analysis.

4 SEISMIC RISK ANALYSIS

By reference to a given seismic site one must consider a specific seismic hazard to evaluate the economic losses for a typological class considered. In particular, it is possible to quantify the costs required to return the building to the condition of structural capacity, and serviceability, before of having suffered the seismic event. More in detail, the seismic losses are determined using the Expected Annual Loss (*EAL*) parameter ([17]). It is corresponded to the measure of the average yearly of having a loss when one correlate the economic consequences, expressed with percent of Reconstruction Cost (*%RC*), whit the occurrence annual frequency, given by the inverse of returning period (λ_{IM}). Firstly, the seismic hazard curve is assumed to be in base seismic condition, where in this case the local amplification effects are not considered (rigid soil type A and horizontal plan T1, [28]).

In this work, the *EALs* are derived starting from the typological economic loss curves seen in Sect. 3.2. Specific economic loss curve may be derived, by referring to a specific law $\lambda = \lambda(IM)$, where is converted the generic IM with a specific average annual frequency of occurrence of a determinate site. It should be noted that for each damage level is derived an economic loss curve, therefore, the total economic loss (EAL_{tot}) is quantified through the summation of every economic loss (EAL_i) of each damage level (D_i). This is reassumed as to follow.

$$EAL_{tot} = \sum_{i=1}^{5} EAL_i = \sum_{i=1}^{5} \%RC_i \int_{0}^{\infty} P(D = D_i|IM) d\lambda_{IM} \tag{5}$$

where λ_{IM} is the average annual frequency of occurrence associated to the specific site hazard curve.

Figure 7 depicts the results of the proposal procedure (5) for derive the specific losses expressed through the total Expected Annual Loss (EAL_{tot}). In particular, it is report in the form of histogram, for each vulnerability class for both building stocks, the economic losses derived by epicentre site of the main shock by L'Aquila 2009 (municipality of L'Aquila, Figure 7a) and Emilia 2012 (municipality of Mirandola, Figure 7b). In this case we have observed that with the same seismic hazard, the vulnerability classes obtained with L'Aquila stock presents greater *EAL* than vulnerability classes of the Emilia 2012 stock.

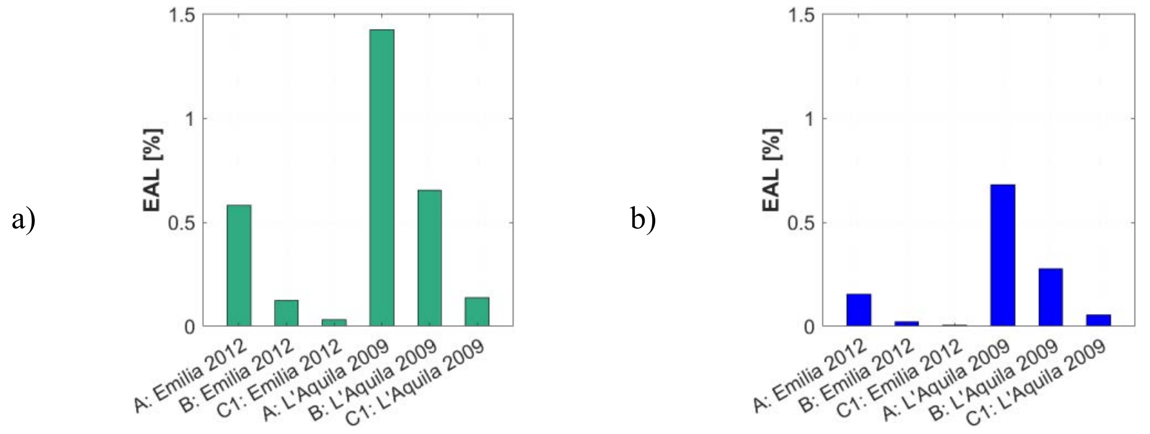

Figure 7: Values of EAL_{tot} from different vulnerability classes derived with L'Aquila 2009 and Emilia 2012 building stocks in a specific epicentral sites: a) L'Aquila; b) Mirandola

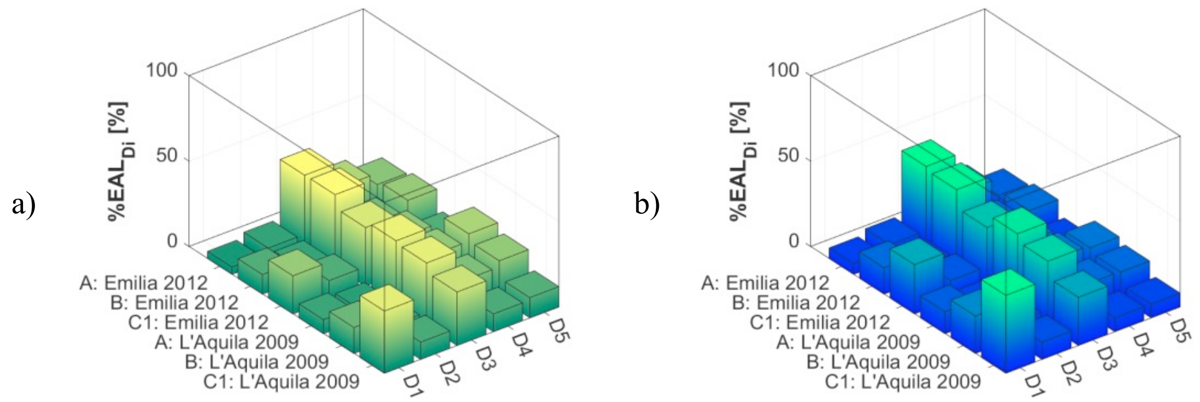

Figure 8: EAL_i contribution for each D_i from different vulnerability classes derived with L'Aquila 2009 and Emilia 2012 building stocks in a specific epicentral sites: a) L'Aquila; b) Mirandola

Finally, it is showed in Figure 8 that thanks to the proposal procedure for derive the economic losses, is possible to quantify the percent contribution of each damage level (D1, D2, …, D5). However, while that the vulnerability classes presents different losses, they have a similar breakdown among damage levels, where for both masonry buildings stocks, is given that D_3 provides the greater percent contribution. Furthermore, for the *Class C1* derived with L'Aquila 2009 stock, in both the L'Aquila and Mirandola site, the greater contribution is given from the damage level D_1 probably caused by the form assumed of the typological economic loss curves at low IM.

5 CONCLUSIONS

In this work, an economic losses analysis has been conducted on damage masonry buildings that have suffered L'Aquila 2009 and Emilia 2012 seismic sequences. Starting to observe damage data, have proposed a procedure for define the typological economic loss curves through the deriving to fragility curves. Furthermore, completion criterion for take into account the influence of the unsurveyed buildings in the municipalities affected by two earthquakes for the stocks considered, available on Da.D.O..

More in detail, a comparison of the typological economic loss curve is carried out and have shown that the vulnerability class *A*, *B* and *C1* of Da.D.O. have not a clear correlation among the two building stocks. In fact, it could probably be due because are presents most different typologies within the vulnerability classes. This is particulary clear observing the breakdown of typological classes according to AeDES form, where they are most different in the building stocks, highlighting the use of different building characteristics, specific to a geographic area. Therefore, as seen, result be too wide this vulnerability classes to be indipendently from the buildings stocks and representative of the structural behaviour of a group of buildings. Then, one should would necessary to refer to multiple seismic events to define the losses for better accounting for the uncertainties in macroseismic analysis.

Regarding seismic risk assessment, it was seen how to quantify the contribution of the specific economic losses of each individual damage level. Starting from typological economic loss curves derived in this study for residential masonry buildings, distributed in the three vulnerability classes (*Class A*, *B* and *C1*) previously defined, considering the epicentral site of the main shock for L'Aquila 2009 and Emilia 2012 earthquake (i.e., L'Aquila and Mirandola, respectively), the EALs was derived. More in detail, was shown that EAL_{tot} obtained for L'Aquila site with respect to Mirandola highlighted greater values.

Anyway, as for the contribution of the EAL_{Di} the results obtained clearly show that the higher contribution within the two buildings stocks is always given by the damage D_3, that may be assumed corresponding to the life safety limit state for buildings, except that for the *Class C1* derived with L'Aquila 2009 stock, where in both the L'Aquila and Mirandola site the greater contribution is given from the damage level D_1 (operativity limit state).

In the future, it will be of interest for various applications concerning the assessment, and mitigation, of seismic risk, identify the contribution within the EAL_{tot} of the EAL_{Di}.

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