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Seismic risk analysis on masonry buildings damaged by L'Aquila 2009 and Emilia 2012 earthquakes

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Abstract

Earthquakes in the recent past continue to provide more and more information on the seismic behavior of existing buildings and on the related economic losses. For the reason it is interesting to compare the damage of buildings stocks archived after earthquakes survey activities.

In this paper a study of the damage occurred on masonry buildings after L'Aquila 2009 and Emilia 2012 earthquakes is carried out, by considering the data available in the web-gis Da.D.O platform.

Firstly, fragility curves are illustrated and compared by considering the vulnerability classes of Da.D.O. (Class A, Class B and Class C1). Then, an approach is proposed in order to evaluate the total Expected Annual Loss (EAL_{tot}) and its contributions due to the several damage level (D_1, …, D_5). The preliminary obtained results show that, with reference to the two masonry buildings stocks considered, the higher contribution to the (EAL_{tot}) is given by the damage level D_3, that may be considered as the life safety limit state. In the case analyzed, the corresponding EAL_{D3} results almost equal to 1/3 of EAL_{tot}.

Keywords: damage assessment; fragility curves; masonry buildings; seismic risk; expected annual loss.

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1. Introduction

In recent years, in Italy the seismic damage suffered by buildings has been collected in several databases, thanks to the survey activities carried out after the seismic events. These data collections have increasingly encouraged the scientific community to tackle the issue of the seismic risk assessment of the existing buildings, as the study of the past seismic damage provides important information on the constructions vulnerability, suggesting how to intervene for mitigating the seismic risk (Braga et al. 1982).

Within this framework, many efforts are continuously done by the scientific community in order to predict damage scenarios of Italian buildings typologies. For instance, among the others, in Del Gaudio et al. (2019) and Zuccaro et al. (2020) fragility curves were proposed by using the damage registered after the L'Aquila 2009 earthquake. In Ioannou et al. (2018, 2021) the seismic damage registered after Emilia 2012 was considered. Finally, in other works, such as in Rosti et al. (2020), several databases of seismic damage were taken into account.

This paper presents some elaborations starting from the damage observed on masonry buildings stocks after the L'Aquila 2009 and Emilia 2012 earthquakes. The observed damages information are available from Da.D.O. (Observed Damage Database) web-gis database (DPC 2015, Dolce et al. 2019) where, for different Italian earthquakes, several information are collected from AeDES forms (Baggio et al. 2007), as well as the characteristics of the seismic event considered. In this study a seismic risk analysis is conducted, by deriving typological fragility curves for masonry buildings. Then, economic loss curves, expressed through the Expected Annualized Loss (*EAL*) (Porter et al. 2004, 2021) for the municipality of L'Aquila and Mirandola are shown. To this scope, preliminary results are shown by applying a method capable to quantify the contribution of each single damage level (EAL_{Di}) in the total economic loss expressed in terms of EAL_{tot}.

2. Damage data collected after L'Aquila 2009 and Emilia 2012 earthquakes

2.1. Buildings stocks considered

Da.D.O. database reports the AeDES forms of 74049 and 22554 surveyed buildings, related to 129 and 55 municipalities, respectively, for L'Aquila 2009 and Emilia 2012 earthquakes. Fig. 1 reports the percentage distribution of buildings having an AeDES form for both earthquakes considered. As it is clear to note, in both buildings stocks the dominant typology is represented by masonry structures: it has a recurrence of 79% in the buildings surveyed after L'Aquila 2009 earthquake, and of 88% in the buildings surveyed after Emilia 2012 earthquake. Whereas, the RC frame structure is less frequent (19% for L'Aquila 2009, 10% for Emilia 2012). Finally, for other construction types the recurrence within the database of the buildings surveyed is less than 1% for both earthquakes.

As for the vulnerability, Fig. 2 reports the percentage repartition for the two buildings stocks considered. As known, Da.D.O. defines three vulnerability classes named Class A, Class B and Class C1 (DPC 2015) with a decrescent vulnerability level from Class A (the most vulnerable) to Class C1 (the least vulnerable). One may note that the case Emilia buildings have a more regular distribution among the three classes with respect to the L'Aquila one, where the Class A results the most frequent (more than 50% of the buildings considered).

2.2. Damage distribution within the two buildings stocks considered

AeDES form presents four seismic 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). These value are in accordance with the EMS-98 damage scale (null damage D_0, slight damage D_1, moderate damage D_2, heavy damage D_3, very heavy damage D_4 and collapse D_5, Grunthal 1998), and have to be assigned to each structural element of the buildings surveyed, such as: vertical structures, floors, stairs, roofs, partitions, and pre-existing damage before the seismic event occurred. Then, starting from the damage assigned to each element, a global damage to the structure may be assigned (DPC 2015, Dolce et al. 2019). In this study, the global damage is assigned following the maximum damage observed among the building components, according to the work of Rota et al. (2008).

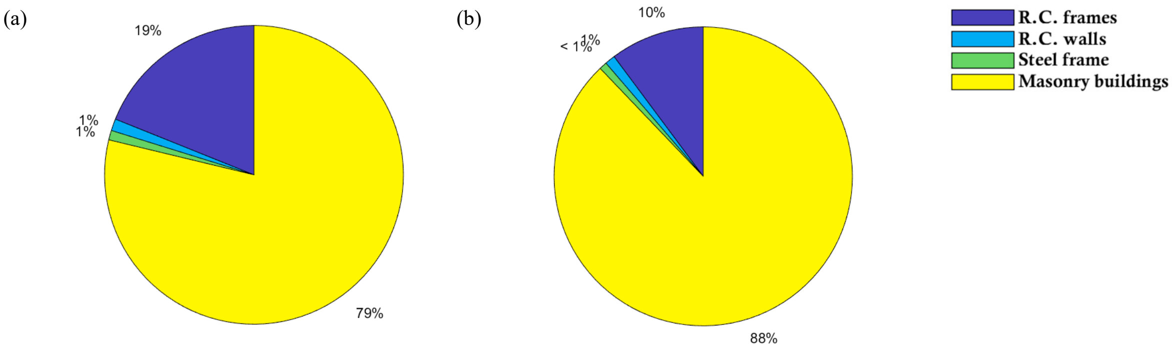


Fig. 1. Construction type percentage distribution for building stocks of: (a) L'Aquila 2009, (b) Emilia 2012 earthquakes.

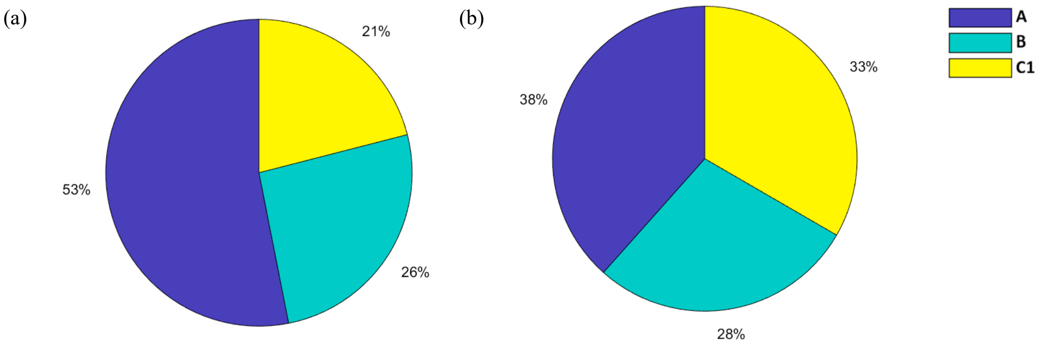


Fig. 2. Vulnerability class percentage distribution for building stocks of: (a) L'Aquila 2009, (b) Emilia 2012 earthquakes

As it is easy to expect, the adopted criterion provides an overestimation of the damage level conducting to a more conservative evaluation of the seismic risk assessment (D'Amato et al. 2020).

Fig. 3 shows in the form of histogram the seismic damage distribution within the masonry buildings stocks of L'Aquila 2009 and Emilia 2012 earthquakes. In the same graph in percentage also the cumulative distribution is reported. The figures highlight those higher damages in masonry buildings are recurrent for the Emilia 2012 earthquake, even if the buildings number is lower than the one surveyed for the L'Aquila 2009 earthquake.

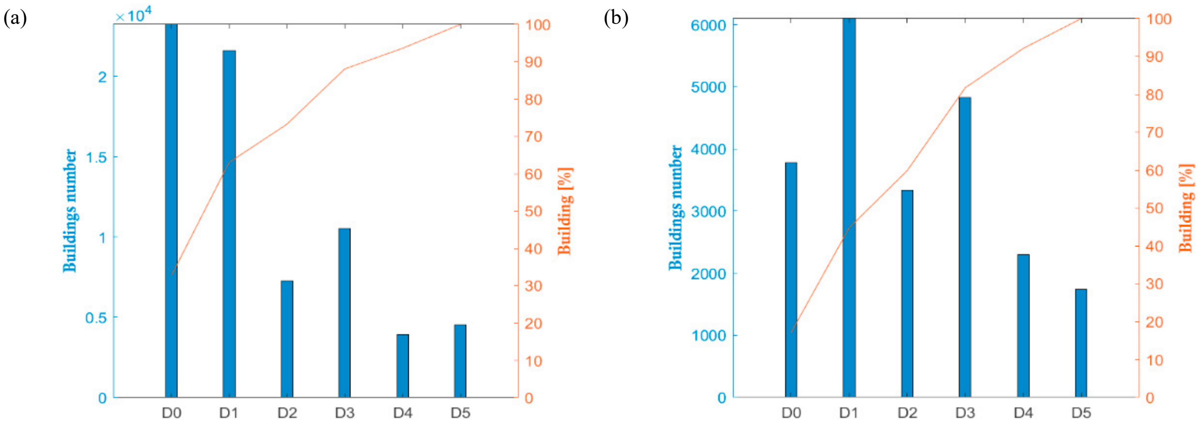


Fig. 3. Damage distribution within the two masonry buildings stocks considered: (a) L'Aquila 2009; (b) Emilia 2012 earthquake.

2.3. Estimation of undamaged buildings

The results presented in the previous section refer to the buildings surveyed in the post-earthquake phases having an AeDES form and archived within the Da.D.O. database. In general, the buildings number surveyed does not represent all the buildings affected by the earthquake analysed, since many buildings may be not surveyed since were not damaged. As proof of this, one may compare the number of buildings belonging to the two buildings stocks considered with the ones registered within the ISTAT 2011 census database (ISTAT 2011) and falling within the municipalities surveyed. In the case analysed ISTAT database, provides 174897 and 139611 buildings recorded, within municipalities surveyed against, respectively, 74049 and 22554 AeDES forms collected for L'Aquila and Emilia 2012 earthquake.

In recent years, several authors have faced the issue of completing the database. In D'Amato et al. (2020, 2022), Laguardia et al. (2022) and Zucconi et al. (2018), it is proposed to evaluate the buildings typological distribution by referring to a completely surveyed municipality, considered as the municipality reference for the completion database. Instead, in Zuccaro et al. (2020), the database completion is performed considering a completeness index evaluated as a function of the PGA.

The approach proposed in this study consists in calculating municipality-by-municipality the number of undamaged buildings for completing the AeDES buildings stock. For each municipality, the buildings number with the AeDES form is compared with the ISTAT 2011 census one, according to the following equation:

$$N_{i.added}^{D0} = N_{i.ISTAT} - N_{i.AeDES}^{D0-D5} \tag{1}$$

where $N_{i,added}^{D0}$ is the undamaged buildings number added for completing the Da.D.O. database for the *i-th* municipality analysed. $N_{i.ISTAT}$ is the total buildings number counted by the ISTAT 2011 census and $N_{i,AeDES}^{D0-D5}$ is the buildings number reported in the Da.D.O. database.

In this study in each municipality the buildings typological distribution within the $N_{i,added}^{D0}$ is assumed equal to the typological distribution resulting from the ISTAT census. Therefore, once the masonry buildings percentage $\%N_{i.ISTAT}^{M}$ is obtained, the undamaged masonry buildings $N_{i,added}^{D0.M}$ for completing the Da.D.O. database may be calculated as follows:

$$N_{i.added}^{D0.M} = \%N_{i.ISTAT}^{M} \cdot N_{i.added}^{D0} \tag{2}$$

Precisely, by applying the approach proposed the added number of undamaged masonry buildings $N_{i,added}^{D0.M}$ is in total of 59874 buildings for L'Aquila and of 107605 for the Emilia building stock. In this way, the completed stock for L'Aquila 2009 and Emilia 2012 is composed, respectively, by 118372 and 127452 masonry buildings.

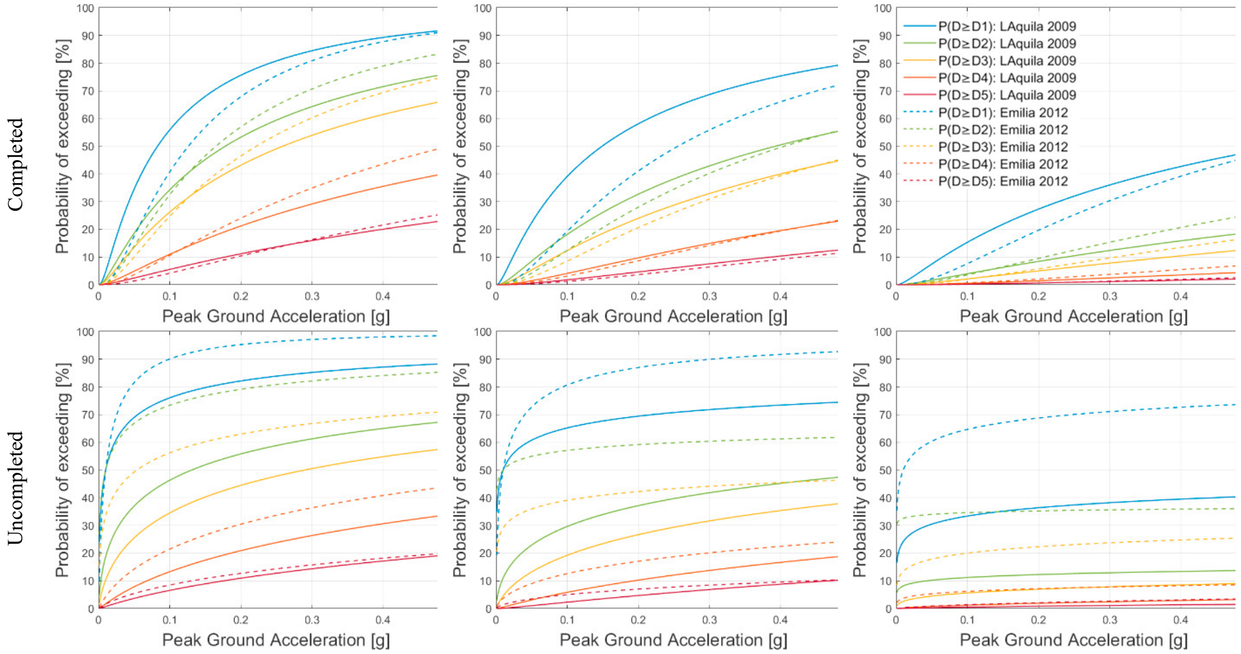
Once the masonry building database is completed, a seismic risk analysis is conducted as it will explained in the next sections.

3. Fragility curves

In this section fragility curves are derived, starting from the building stocks completed with the undamaged buildings as previously described.

In general, a fragility curve is statistical distribution indicating the conditional probability of having an event equal to or greater than a predetermined event for a given demand value. As for civil engineering applications, the predetermined events are the damage levels expressed by EMS-98, while the demand value is represented by an Intensity Measure (*IM*), such as for instance the Peak Ground Acceleration (*PGA*). The fragility function is representing through a lognormal cumulative distribution, see Eq. (3):

$$P_{D\geq D_i} = P(D \geq D_i) = \Phi\left(\frac{\ln\left(\frac{IM}{\vartheta}\right)}{\beta}\right) \quad i = 0, \ldots, 5 \tag{3}$$



(a) Class A (b) Class B (c) Class C1

Fig. 4. Comparison between typological fragility curves for masonry buildings from Emilia 2012 and L'Aquila 2009

where $P_{D\geq D_i}$ is the fragility function for the i-th damage conditioned to an intensity measure. Φ is the standard normal cumulative distribution function of $ln\,(IM/\vartheta)/\beta$, where ϑ and β are respectively the median value and the standard deviation of the logarithm of *IMs*. The parameters ϑ and β may be derived with the maximum likelihood criterion, where the likelihood function is Baker (2015):

$$\mathcal{L}(\vartheta,\beta)=\prod_{j=1}^{m}\binom{k_j}{n_j}\Phi\left(\frac{\ln\left(\frac{IM}{\vartheta}\right)}{\beta}\right)^{k_j}\left[1-\Phi\left(\left[\frac{\ln\left(\frac{IM}{\vartheta}\right)}{\beta}\right]\right)\right]^{n_j-k_j} \quad j=1,\dots,m \tag{4}$$

where the binomial probability distribution is assumed for calculating the probability of observing k_j buildings with a damage equal or greater than a specific value; n_j is the number of buildings falling in the *j-th* interval having an intensity measure ΔIM_j.

Hence, the parameters ϑ and β for each fragility function are obtained by maximizing the logarithm of the likelihood function, which is expressed with:

$$\left(\hat{\vartheta},\hat{\beta}\right)=arg\,max\sum_{j=1}^{m}\left\{ln\binom{k_j}{n_j}+k_j ln\left[\Phi\left(\frac{\ln\left(\frac{IM}{\vartheta}\right)}{\beta}\right)\right]+(n_j-k_j)ln\left[\Phi\left(\frac{\ln\left(\frac{IM}{\vartheta}\right)}{\beta}\right)\right]\right\} \quad j=1,\dots,m \tag{5}$$

where $\left(\hat{\vartheta},\hat{\beta}\right)$ correspond, respectively, to the median value and the standard deviation of the logarithm of *IMs*, allowing to have the most likely fragility curve.

In Fig. 4 the derived fragility curves for the different masonry vulnerability classes are reported. In particular, Fig. 4(a) refers to Class A, Fig. 4(b) to Class B and Fig. 4(c) to Class C1. The curves derived for buldings stocks of Emilia 2012 are indicated with a dashed line, while with a solid line are reported the curves referred to the L'Aquila 2009 building stocks. As one may observe the fragility curves obtained it not possible to identify a clear correlation among the curves of L'Aquila and of Emilia. This may be due to the fact that the vulnerability classes adopted by Da.D.O. are too wide, including within the same class different sub-typologies of masonry buildings. In addition, it would be necessary to refer to multiple seismic events for better accounting for the uncertainties in defining the typological fragility curves. Finally, particular attention should be given to the masonry typology, taking into account the specific characteristics of the material and of the construction details in a specific geographical area. These aspects will be investigated more in detail in future.

In order to illustrate the influence of the completion databse, Fig. 4 reports as well the fragility curves obatined by referring to the uncompleted database, i.e. deriving the fragilities curves only referring to the damage database available from Da.D.O. It is quite clear that these curves, with respect to the completed ones, are significantly different and highliting that the choice of the appropriate criterion for better reproducing the sample of buildings investigated plays a central role in seismic risk analysis. Anyway, this aspect will be invetsigated more in detail in future works.

4. Seismic risk curves

The seismic risk analysis permits to quantify the economic losses caused by a seismic event occurring in a site, in a certain time interval. In this way it is possible to quantify the costs necessary to restore the construction before of a seismic event, accepted a probability of having a certain damage level. The parameter used to quantify the seismic loss is represented by the Expected Annualized Loss (*EAL*). It measures the average yearly amount of loss when one accounts for the frequency and severity of various levels of seismic events, given by the area enclosed by the loss curve (Porter et al. 2004).

In this work, the following procedure to derive the loss curves the EALs is proposed, summarized as follows:

- evaluation of the damage probability curves $P(D = D_i|IM)$ (*i=1, ...,5*), derived from fragility curves;
- evaluation of the typological economic loss curves $L_{D_i}(D = D_i|IM)$ (*i=1, ...,5*). These curves are derived by using the consequence correlations expressed in terms of Reconstruction Cost percentage (*%RC*) for each damage level according to (Ministerial Decree n. 58). These curves are independent on a specific site seismic hazard;
- starting from the typological economic loss curves $L(D = D_i|IM)$ (*i=1,...,5*), specific economic loss curves $L_{D_i}(D = D_i|\lambda(IM))$ may be derived, by referring to a law $\lambda = \lambda(IM)$ specific for the reference site, where λ_{IM} is the average annual frequency of occurrence to each intensity measure;
- evaluation of the total EAL_{tot} through the sum of partial EAL_i, that is the economic loss (expressed as *%RC*) related to *i-th* damage level D_i, given by the following summation:

$$EAL_{tot} = \sum_{i=1}^{5} EAL_i = \sum_{i=1}^{5} \int L_{D_i}(D = D_i|\lambda(IM)) \qquad (6')$$

$$EAL_{tot} = \sum_{i=1}^{5} EAL_i = \sum_{i=1}^{5} \%RC_i \int_0^{\infty} P(D = D_i|IM) d\lambda_{IM} \qquad (7'')$$

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

Following the procedure proposed, the resulting seismic loss curves are plotted in Fig. 5, with the frequencies related to return periods of 30, 50, 475 and 975 years of the ordinary buildings limit states in accordance with Italian Design Code (NTC 2018). In general, the Vulnerability Class C1, the least vulnerable, presents a quite flat trend if compared with the Class A, having higher *%RC* values for low occurrence value. The EAL_{tot} results higher for the three classes of masonry buildings of L'Aquila, having a site seismic hazard higher with respect to the Emilia epicenter municipality (in this case corresponding to Mirandola municipality). In this case we have that for buildings of Class A the EAL value derived for L'Aquila is of 1.55%, that is three times greater than the one found in the case of Emilia.

Fig. 6 reports in the form of histogram the partition of the obtained EAL_{tot} in the contribution EAL_{Di} due to each damage level. As one may clearly one the greater percentage contribution, for both masonry buildings stocks, is given for the damage level D_3: in this case percentage of 37.7% and 41.9% are found. Lower percentages are obtained for D_1 and D_2 with percentage contributions always lower than 15%, with except for the damage D_1 of type Class C1 for L'Aquila buildings.

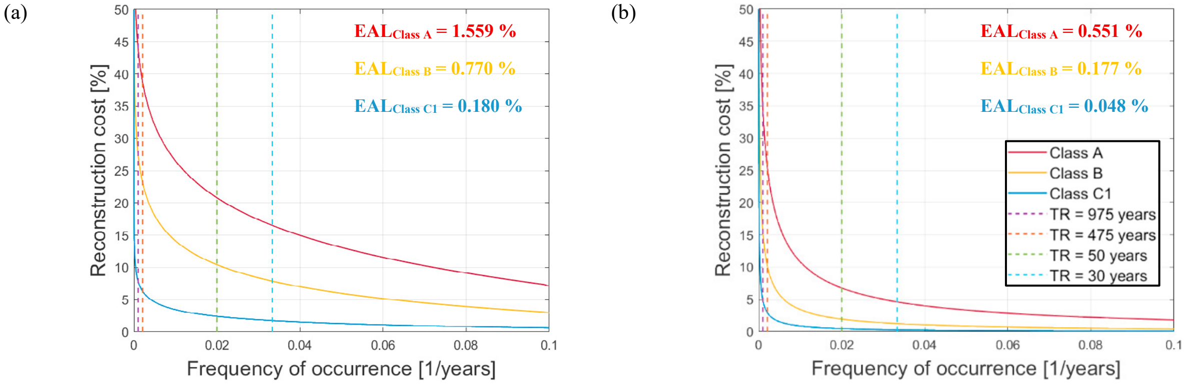


Fig. 5. Seismic loss curves by considering differently vulnerability classes: (a) L'Aquila 2009, (b) Emilia 2012

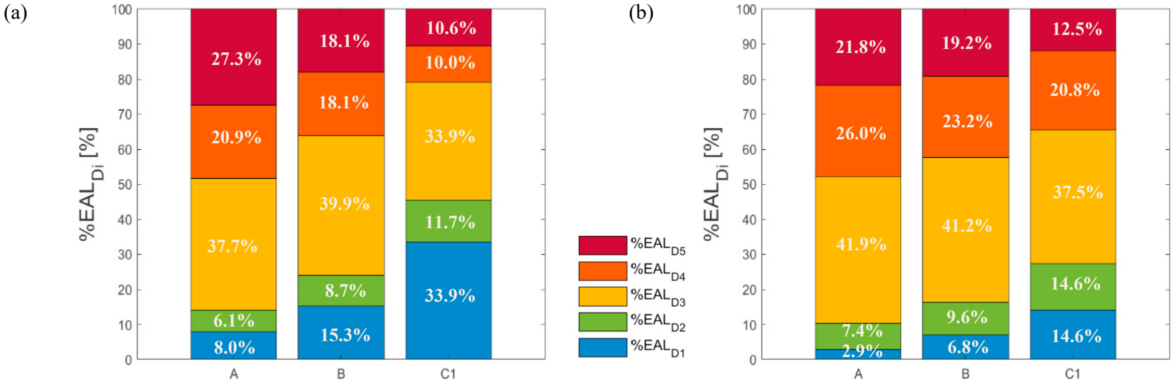


Fig. 6. EAL$_i$ contribution for each D$_i$ from different vulnerability classes: (a) L'Aquila 2009 (b) Emilia 2012

5. Conclusions

In this work, seismic losses for masonry buildings have been estimated starting from the damage observed after L'Aquila 2009 and Emilia 2012 earthquakes. To this scope fragility curves have been proposed, also considering a completion of the two buildings stocks available on Da.D.O. In this way the influence of the undamaged and not inspected buildings in the municipalities affected by the two earthquakes has been taken into account, too.

The results observed from the comparison of the fragility curves have shown that the vulnerability classes of Da.D.O. (Class A, Class B and Class C1) are not fully comparable for the two buildings stocks considered. This could potentially be due to the fact that these vulnerability classes are too wide, and they do not permit a clear comparison among the two buildings stocks. Moreover, within the same building stocks it would be necessary to refer to multiple seismic events to define the typological fragility curves for better accounting for the uncertainties in macro-seismic analysis. Finally, particular attention should be given to the masonry typology, considering the specific characteristics of the material and of the construction details in a specific geographical area.

A method has been proposed for calculating the total EAL_{tot} and the contributions due to the different damage levels. In this way to it is possible to quantify the contribution of each single damage level in the risk assessment analysis. The economic losses have been derived starting from typological economic loss curves derived in this study for masonry buildings classified in three vulnerability classes (A, B, C1), and referring to L'Aquila and Mirandola municipality for the two seismic events considered. The comparison of EAL_{Di} values highlights that in the case analyzed a higher EAL_{tot} is obtained for L'Aquila site with respect to Mirandola. 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.

Starting from the seismic risk procedure proposed, in future several applications will be conducted in over to estimate the EAL_{tot} for different construction typologies, with a particular interest to identify the contribution within the EAL_{tot} of the EAL_{Di}.

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