ASSOCIAZIONE NAZIONALE ITALIANA DI INGEGNERIA SISMICA ANIDIS
Italian National Association of Earthquake Engineering
XVIII CONVEGNO ANIDIS
L'ingegneria sismica in Italia
ASCOLI PICENO 2019
15-19 Settembre

The influence of retrofit intervention on vulnerability of masonry buildings from post-earthquake damage data of the last 50 years

Carlo Del Gaudio, Santa Anna Scala, Paolo Ricci, Gerardo Mario Verderame
Department of Structures for Engineering and Architecture, Via Claudio, 21 - 80125 Naples - Italy

Keywords:

Fragility curves, masonry buildings, AeDES form, EMS-98, damage data, strengthening interventions

ABSTRACT
The post-earthquake damage data of last 50 years (from Friuli 1976 to Emilia 2012) recently released by the Italian Department of Civil Protection through the online platform Da.D.O. are used in this paper to derive vulnerability curves for the Italian residential building stock. 9 Seismic events of national interest (Friuli 1976; Irpinia 1980; Abruzzo 1984; Umbria-Marche 1997; Pollino 1998; Molise 2002; Emilia 2003; L'Aquila 2009; Emilia 2012) have been considered.
Macro-seismic intensity values for each Municipality are evaluated from Macro-seismic database relative to each event (Rovida et al., 2016).Census data relative to locations with Macro-seismic intensities less than 4, resulting undamaged according to the European Macro-seismic Scale EMS-98 (Grünthal, 1998) classification, are used in combination with post-earthquake data in order to avoid any bias in fitting procedures.
Vulnerability curves are derived considering Macro-seismic intensity values and observed damage only for vertical structures. Different structural typologies have been considered as a function of structural typologies (seismic and gravitational) and the presence of retrofit interventions and the comparison between the curves is used to prove their effectiveness.

1 INTRODUCTION

The purpose of this study is the evaluation of effectiveness of retrofit interventions on masonry buildings through the derivation of empirical vulnerability curves from damage data. To this aim, data from post-earthquake surveys of last 50 years (Friuli 1976; Irpinia 1980; Abruzzo 1984; Umbria-Marche 1997; Pollino 1998; Molise 2002; Emilia 2003; L'Aquila 2009; Emilia 2012) collected by the Italian Department of Civil Protection and recently released through the online platform Da.D.O. will be used. The influence of strengthening interventions on vulnerability of existing buildings has been already addressed in previous studies. For example, in (Sisti et al., 2018), the effectiveness of these interventions has been shown for historical centre of Norcia through AeDES forms (compiled after 2016 Central Italy earthquake) related to 670 residential masonry buildings. In (Zucconi et al., 2018), the influence of strengthening interventions on usability trends for 4 different structural typologies have been investigated for masonry buildings damaged after 2009 L'Aquila earthquake.

Similarly, the influence of traditional reinforcement (i.e. timber tie, wrought iron cross tie inserted in a quoin and twentieth century steel tie with end plate) on damage mechanism has been investigated by (D'Ayala and Paganone, 2010), considering the results of a survey carried out in the towns of Paganica and Onna in the district of L'Aquila, affected by 2009 April 6th earthquake.

In this study, mean damage trends with Macro-seismic intensity values, obtained for each Municipality from (Rovida, 2016), will be derived. Thus, 5+1 damage levels will be defined according to European Macro-seismic Scale EMS-98 (Grünthal, 1998) from observed damage for vertical structures collected during the inspections. Lastly, vulnerability curves for different structural typologies, namely gravity load designed buildings (those constructed before seismic classification of the site), seismic load designed buildings (those constructed thereof) and retrofitted buildings (those constructed before seismic classification of the site and subjected to retrofit intervention thereof) will be derived and their comparison will be used to prove the effectiveness of retrofit intervention.

2 THE DA.D.O. PLATFORM AND CRITICAL REVIEW OF POST-EARTHQUAKE DATA

The DPC, with the support of Eucentre, provided an informatics platform, called Da.D.O., which allows the access to a large database of the damage suffered by buildings after the main earthquakes occurred in Italy in the last 50 years. This database, which considers the last 9 seismic events of national relevance occurred in Italy (Friuli 1976; Irpinia 1980; Abruzzo 1984; Umbria-Marche 1997; Pollino 1998; Molise 2002; Emilia 2003; L'Aquila 2009; Emilia 2012), can represent a useful support in the forecasting and mitigation policies against earthquakes.

Generally speaking, soon after the earthquake the DPC manages and carries out, with the support of technicians from different institutions and professional organizations, an in-situ survey campaign of all the buildings sited in the affected areas, to define the safety level of each damaged building, considering also the possible occurrence of aftershock.

Thus, after each event, the main information about location and morphological-functional characteristics of the building, about the observed damage are collected. Additionally, information about losses (victims, injured, homeless), Macro-seismic intensity values at Municipality level and sometimes even for specific location, about the magnitude of the event and the location of the hypocentre are reported.

The quantity and the quality of the information collected after the 9 considered events result very different, essentially due to substantial changes in the different survey forms used during the inspections. Nevertheless, the DPC with the support of Eucentre has spent huge efforts in the homogenization process of all parameters collected through the years in order to make them comparable between all the 9 considered events.

In general, the parameters collected in the platform relative to each seismic event can be grouped in different macro-sections:

- *Building identification*: information about the municipality where each building sited and its position;
- *Building description*: number of storeys, inter-storey, storey surface area, construction and retrofit (if any) ages;
- *Building typology*: information on vertical and horizontal structures, on the presence of tie rods or tie beams, of isolated columns, on mixed type structures.
- *Damage*: the data on damage strongly depends on the survey form used after each seismic event. For example, for Irpinia 1980 the damage database contains (7+1) damage levels (including the null damage) while for Abruzzo 1984 the damage levels are (5+1), coherently with the European Macro-seismic Scale EMS-98 (Grunthal, 1998). Starting from the Umbria-Marche 1997 event, the first level AeDES survey form for post-earthquake damage and usability assessment was used (Baggio et al., 2007), considering (3+1) damage levels. Moreover, starting from Irpinia 1980, the damage database contains data for three or more structural components and only from Umbria-Marche 1997 also the damage extension is taken into account.

Table 1. Structural typologies of the (all and residential) buildings reported in Da.D.O. for each available databases.

Seismic Event	Buildings				Residential Buildings			
	Masonry	RC	Others	TOT	Masonry	RC	Others	TOT
Friuli 1976	29641	469	11742	41852	29641	469	11742	41852
Irpinia 1980	30033	3868	4178	38079	30033	3868	4178	38079
Abruzzo 1984	46763	2092	2962	51817	46763	2092	2962	51817
Umbria-Marche 1997	41852	50	6623	48525	34150	31	5323	39504
Pollino 1998	14515	1285	1642	17442	11708	1086	1507	14301
Molise 2002	19086	2206	2849	24141	16485	1713	1842	20040
Emilia 2003	899	0	112	1011	808	0	95	903
L'Aquila 2009	49365	12019	12665	74049	42122	10370	10310	62809
Emilia 2012	17881	1795	2878	22554	12711	982	1949	15642
TOT	250035	23754	45651	319470	224428	20611	39908	284947

Table 1 shows the number of buildings available for each database, subdivided as a function of structural types. About 80% of the population is constituted by masonry buildings, while only 8% by RC buildings and the remaining 12% by other types (steel, mixed,…). Moreover, hereinafter only a subset of 224428 masonry buildings will be considered, characterized by a residential use. For what concerns masonry buildings, 40% of the total is represented by Abruzzo 1984 and L'Aquila 2009 databases. On the other hand, about 70% of the RC buildings is represented by Irpinia 1980 and L'Aquila 2009 databases. Note that Emilia 2003 database is constituted by very few buildings (only 0.4% of masonry buildings and no RC buildings, respectively). Moreover, Umbria-Marche 1997 database reports a significant number of masonry buildings (similar to Abruzzo 1984 and L'Aquila 2009 databases), and a limited number of RC buildings (just 0.2% of the total).

Herein a selection of the original amount of data (see Table 1) regarding masonry buildings will be done, to obtain a reliable subset of data for fragility analysis. Firstly, only database which parameters (especially for damage information) can be effectively comparable each other will be considered: i.e. for Friuli 1976 database, no information on damage for structural components is reported, but only regarding the entire building, unlike the remaining database. Therefore, Friuli 1976 database will be discarded in what follow in order to avoid mismatching in damage classification. Secondly, only database characterized by complete sample of data will be considered. Thus, for each database and for each municipality a completeness ratio, CR, will be defined as the ratio between the number of inspections contained in the Da.D.O. platform and the number of residential buildings contained in census data (ISTAT). Obviously, the lowest is the CR the highest is the number of not inspected buildings; conversely when CR approaches to 1 (or overcomes 1) it means that all the buildings sited in that municipalities have been inspected. It is to be noted that a partial or incomplete subset of buildings (CR << 1), if not statistically representative of the damage suffered by buildings of that area could strongly biases fragility estimation (Rossetto et al., 2013). Thus, Emilia 2003 database, which is constituted by very few buildings (only 0.4% of masonry buildings and no RC buildings, respectively), will be discarded from following elaborations. Therefore, out of the 9 databases included in Da.D.O. platform, only Irpinia 1980, Abruzzo 1984, Umbria-Marche 1997, Pollino 1998, Molise 2002, L'Aquila 2009 and Emilia 2012 databases will considered in this study. In these databases, it can occurs that in the area near the epicenter a complete (building-by-building) survey was done, whereas in the area farthest from the epicenter the inspections were done only under the building owner's request, for example for Molise 2002 database (Goretti and Di Pasquale, 2004). This represent a critical circumstance, since in this area (farthest from the epicenter) mainly damaged buildings were inspected, systematically neglecting undamaged ones.Then, if these data will be used for fragility assessment without further elaborations, biases in fragility curves could be introduced. To this aim, (Rossetto et al., 2013) summarizes the possible solutions adopted in literature to overcome this problem. The first solution deals with the removal of all the data regarding to buildings sited in a municipality characterized by a CR value below a predefined threshold. Values of completeness threshold reported in previous studies are of the order of 0.75 (Sabetta et al., 1998), 0.80 (Goretti and Di Pasquale, 2004), 0.60 (Rota et al., 2008). The second solution consists of the identification of incomplete subsets and their integration using census data, considering this additional source as characterized by no-damage to any structural components.

In this study a mixed approach will be used. Firstly, buildings sited in municipalities characterized by a CR value greater than a predefined threshold included in Da.D.O. platform will be used to represent the positive evidence of damage. The value of completeness threshold used in this study is equal to 0.91 according to (Del Gaudio et al., 2019), where the same building dataset used herein has been considered. Then, buildings located in the all municipalities used for macro-seismic analysis (Rovida et al., 2016) and characterized by an intensity less than V will be used to account for the negative evidence of damage. To this aim, the number of residential buildings located therein is taken from census data and no-damage will be assigned to each of them according to EMS-98' classification. The evaluation of CR was carried out considering the data provided by ISTAT 2001 census. It is to be noted that the census date is, in some cases, not coeval to those when the inspection took place, for example for Abruzzo 1984 (17 year before), for L'Aquila 2009 (8 years later) and for Emilia 2012 (11 years later). The use of ISTAT 2001 census is motivated by *(i)* the fact that is about in the middle of the range defined by the occurrence of considered earthquake (from 1980 to 2012), *(ii)* the buildings constructed in the decade 2001-2011 for the considered area are substantially negligible (evaluated using the updated version of census data, ISTAT 2011) and *(iii)* the earlier version of census (ISTAT 1991) deals with a structural unit that is not consistent with that of the survey (dwelling), introducing further uncertainties for their conversion (Colombi et al., 2008).

Obviously, the use of ISTAT 2001 suits good for 1997 Umbria-Marche, 1998 Pollino and 2002 Molise databases. Then, for Abruzzo 1984 the following approach will be used to obtain a reliable comparison between the considered sources (Da.D.O. and ISTAT 2001). Firstly, only buildings from ISTAT 2001 constructed before 1981 will be considered. Then, the number of collapsed buildings (from Da.D.O.) will be added to this sample to account for those demolished between 1984 and 2001 (Colombi et al., 2008). Note that this analysis will not be made for Irpinia 1980 database, since all 41 municipalities reported in Da.D.O. have been chosen by the DPC among the over 600 affected by the 1980 earthquake to be subjected to complete investigations (Braga et al., 1982) as representative of the isoseismals to which they belong.

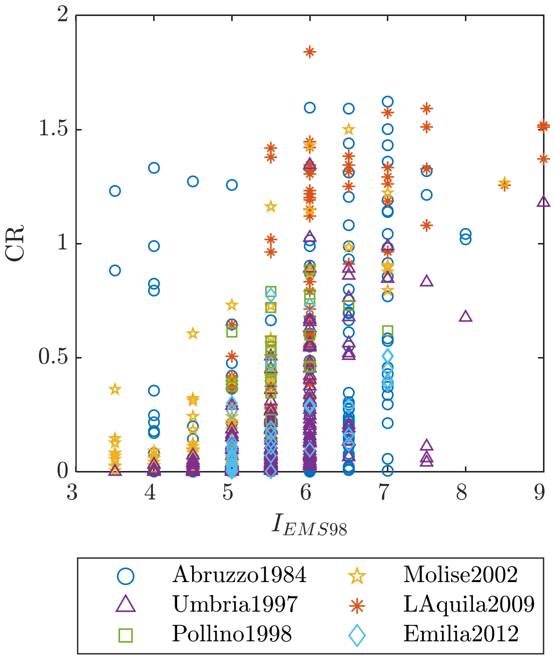

Figure 1. CR for all municipalities of each database (DB)

Figure **Errore. L'origine riferimento non è stata trovata.**1 shows the distribution of the CR for the six considered databases. Note that Abruzzo 1984, Umbria-Marche 1997, Molise 2002 and L'Aquila 2009 databases present at least some municipalities with CR higher than 0.91, which will be considered in this study, whereas Pollino 1998 and Emilia 2012 does not present any municipalities with CR higher than 0.91. Thus, the latters will be discarded, leading to a significant reduction in the number of available data. Ultimately, the databases considered for the derivation of vulnerability curves are Irpinia 1980, Abruzzo 1984, Umbria-Marche 1997, Molise 2002 and L'Aquila 2009. These data, which amount to 90897 out of the 224428 originally considered, represent the positive evidence of damage, coming from post-earthquake inspections. They will be integrated with undamaged buildings, which amount is taken from ISTAT 2001 census data, considering only the municipalities used for macro-seismic analysis and characterized by an intensity less than V. As a matter of fact, according to EMS-98 definition, the location characterized by I_{EMS}< V are characterized by no-damage for all considered vulnerability classes. The integration of these data, which amount to 600866, allows to reduce potential biases in fragility estimation caused by the damage overestimation for the systematically neglecting of undamaged buildings during the survey campaign in the area farthest from the epicenter. Obviously only buildings constructed before 1981 according to ISTAT 2001 will be added for Irpinia 1980 and Abruzzo 1984 databases.

Note that in Figure 1, for some Municipalities CR higher than 1 can be observed. This means that, in these cases, the number of buildings according to ISTAT data is lower than those inspected. This circumstance could be ascribed to the different criteria adopted to identify the structural units during the inspections (presence of seismic expansion joints, structural aggregates).

3 DATA ANALYSIS BASED ON DESIGN TYPOLOGIES AND RETROFIT INTERVENTIONS

In previous section the criteria chosen to select building dataset from all the available databases collected and published by the DPC in the Da.D.O. platform after the 9 seismic events of national relevance occurred in Italy in last 50 years have been defined. In this section, the final datasets will be analyzed for what concern design typologies and retrofit interventions.

The definition of design typologies will be made by comparing construction age of each building with the first seismic classification of the Municipality where it is sited. To this aim, the software package ECS-it, *Evolution of the Italian Seismic Classification* (Del Gaudio et al., 2015) will be used, allowing the definition of the seismic classification of each municipality of Italian territory considering all (over 37) the classification codes enforced since 1909 to 2015. Clearly, if the construction age precedes the year of the first seismic classification, the building was designed to take into consideration only gravity loads, GD; vice versa the building was designed taking into consideration also seismic loads, SD.

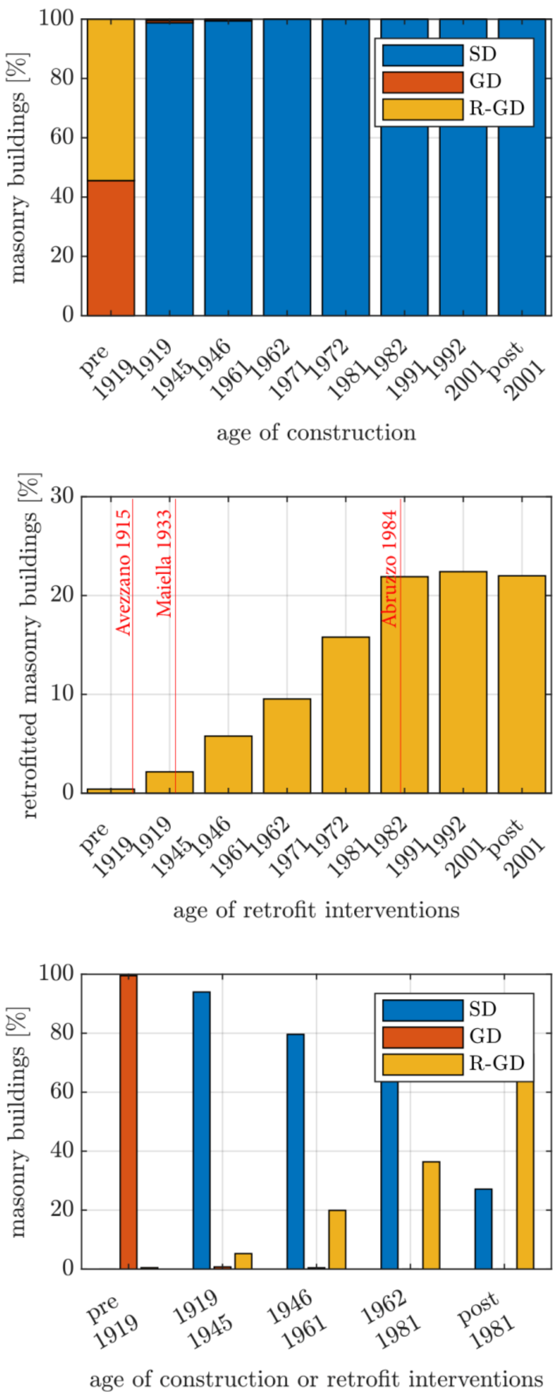

Figure 2. L'Aquila2009 DB: percentage of buildings for each class to varying construction or re-construction age.

Thus, this criteria applied to the considered databases leads to the following statistics:

- *L'Aquila 2009 database*: about 41% of residential masonry buildings was SD and 57% was GD (the 2% remaining was not classified, since no information about construction age was retrieved);
- *Irpinia 1980 database*: about 7,5% of residential masonry buildings was SD and 89,5% was GD;
- *Molise 2002 databases*: about 2,5% of residential masonry buildings was SD and 95% was GD;
- *Abruzzo 1984 database*: about 63% of residential masonry buildings was SD and 27% was GD;
- *Umbria-Marche 1997database*: about 23% of residential masonry buildings was SD and 75% was GD.

Note that all considered municipalities of L'Aquila 2009 database (except *Calascio*, *Campotosto* and *San Benedetto in Perillis*) have been classified for the first time as seismic in 1915. Thus, GD buildings were basically constructed before 1915, whereas SD buildings thereafter. Similarly, about 88% of GD masonry buildings of Abruzzo 1984 database was built before 1900. Therefore, for both databases, GD ones are the most ancient buildings.

In addition, due to all the seismic event occurred in the 20th century, namely the 1915 Avezzano and 1933 Maiella earthquakes, several GD masonry buildings have been subjected through the years by several retrofitting intervention, strongly influencing their attitude to damage. Unfortunately, the information about the age when such kind of intervention was made is only available after 2002 Molise earthquake. According to collected information, more than 50% of GD masonry buildings of L'Aquila 2009 database has been subjected to structural retrofit (see Figure 2). In addition, when the retrofit intervention took place, it happened in more than 65% of cases after 1980 (probably after 1984 Abruzzo earthquake). Accordingly, 40% of the GD masonry buildings of the Molise 2002 database has been subjected to structural retrofit and, if any, in the 55% of cases it was made after 1980.

Lastly, 3 different building classes will be introduced herein, firstly dividing all the buildings as a function of their design typologies (GD and SD), and then considering the contribution that the retrofit interventions, if any, have on vulnerability. Therefore, the third class (R-GD) includes all GD buildings subjected to structural retrofit.

Table 2. Building Classes for each DB.

<table>
<tr><th>DB</th><th>GD</th><th>R-GD</th><th>SD</th></tr>
<tr><td>Irpinia1980</td><td colspan="2">26870</td><td>2267</td></tr>
<tr><td>Abruzzo1984</td><td colspan="2">13269</td><td>6707</td></tr>
<tr><td>Umbria-Marche1997</td><td colspan="2">1220</td><td>368</td></tr>
<tr><td>Molise2002</td><td>4759</td><td>3172</td><td>203</td></tr>
<tr><td>L'Aquila2009</td><td>7541</td><td>9014</td><td>11850</td></tr>
</table>

4 VULNERABILITY CURVES

In this section, the procedure adopted to derive the vulnerability curves starting from observed damage data will be explained. To this aim, the definition of conversion scheme of damage states for considered survey form has to be provided. Then, lognormal vulnerability curves though an optimization technique from the observed damage data will be derived.

4.1 Definition of damage states

Damage levels were defined according to EMS-98, considering 5+1 levels (from DS0 – no damage - to DS5 - collapse). The damage conversion rule proposed by (Rota et al., 2008) was used to convert the level of damage for vertical structures reported in the survey forms into the considered scale (Table 3), providing a uniform and homogenized definition between the several versions used through the years.

Table 3. Scheme of conversion of the damage levels for vertical structures into the EMS-98 Damage State

EMS 98			**Irpinia 1980**		**Abruzzo 1984**		**AeDES**	
Damage level	Damage Description		Damage level	Damage Description	Damage level	Damage Description	Damage level and extension	Damage Description
DS0	No Damage	-	**L1**	No damage	**0**	No damage	**D0**	No damage
DS1	Negligible to Slight damage	*Fine cracks in plaster over frame members or in walls at the base.*	**L2** **L3**	Negligible damage *Unhurried reparation*	**1**	Slight damage	**D1** (<1/3) **D1** (1/3 – 2/3) **D1** (>2/3)	Slight
DS2	Moderate damage	*Cracks in columns and beams of frames and in structural walls.*	**L4**	Substantial damage *Partial evacuation needed* *Repairable*	**2**	Significant damage	**D2-D3** (<1/3)	Medium - severe
DS3	Substantial to Heavy damage	*Cracks in columns and beam column joints of frames […].*	**L5**	Heavy damage *Evacuation needed* *Repairable*	**3**	Severe damage	**D2-D3** (1/3 – 2/3) **D2-D3** (>2/3)	Medium - severe
DS4	Very heavy damage	*Large cracks in structural elements […]; Collapse of a few columns or of a single upper floor.*	**L6**	Very heavy damage *Evacuation and demolition needed*	**4**	Very severe damage	**D4-D5** (<1/3) **D4-D5** (1/3 – 2/3)	Very heavy
DS5	Destruction	*Collapse of ground floor or parts of buildings.*	**L7** **L8**	Partial structural failure *Demolition needed*	**5**	Destruction	**D4-D5** (>2/3)	Very heavy

4.2 Definition of vulnerability curves

In this study, mean damage function μ_D, obtained as weighted average of the damage's distribution, will be adopted for vulnerability assessment:

$$\mu_{D,j} = \frac{\sum_{i=0}^{5} N_{Ed,j}(DS = ds_i)i}{\sum_{i=0}^{5} N_{Ed,j}} \qquad (1)$$

where $N_{Ed,j}(DS=ds_i)$ is the number of buildings characterized by a i^{th} damage level $DS=ds_i$; $N_{Ed,j}$ is the total number of buildings subjected to j^{th} intensity measure.

Generally, EMS-98 macro-seismic intensity values used for vulnerability fitting are taken from (Rovida et al., 2016), except for Irpinia1980 database, where the MSK macro-seismic intensity values are taken from (Braga et al, 1982), assuming the equivalence between the scales, as done in (Dolce and Goretti, 2015).

Then, the parameters defining the vulnerability curves are obtained using the LSE optimization technique (*Least Square Estimation*), minimizing the sum of the squares of the error between observed damage and lognormal cumulative function used to evaluate predicted mean damage values:

$$\arg\min_{\mu,\beta}\left[\sum_j p(I_{EMS98},\mu,\beta) - \frac{\mu_{D,j}}{5}\right]^2 N_{Ed,j} \qquad (2)$$

In (2), the functional form p is the CDF of a log-normal distribution characterized by logarithmic mean μ and standard deviation β. Furthermore, in order to take into account the inhomogeneity of the databases in terms of the number of buildings subject to the j value of macro-seismic intensity, weighed fitting procedure has used, where the weight are the number of buildings, $N_{Ed,j}$.

5 INFLUENCE OF THE RETROFITTING OPERATIONS TROUGH THE VULNERABILITY CURVES

In this section, the effectiveness of retrofit interventions performed through the years in masonry buildings will be analyzed comparing the corresponding vulnerability curves.

Note that not for all the databases this information is available after the inspections. Overall only for Molise 2002 and L'Aquila 2009 ones, information about the presence of retrofit intervention and its age are collected (see Table 2).

L'Aquila 2009 database reports all defined structural typologies: GD buildings (those constructed before seismic classification of the site), SD buildings (those constructed thereof) and retrofitted buildings (R-GD, namely those constructed before seismic classification of the site and subjected to retrofit intervention thereof). Thus, firstly the vulnerability curves for the 3 structural typologies (GD; SD; R-GD), further subdivided considering also the horizontal and vertical types, will be shown for L'Aquila 2009 database. Then, the latter assumed as reference, will be compared to the remaining SD buildings (coming from Abruzzo 1984 database) and GD buildings (coming from Irpinia 1980, Abruzzo 1984 and Molise 2002 databases). Instead, Umbria-Marche 1997 database is too poor to derive vulnerability curves for each structural type: then, the only available typology (GD buildings) not will be considered. Moreover, in order to compare data related to distant in time seismic events, only buildings constructed before 1980 will be used to derive the curves.

5.1 *Vulnerability assessment for L'Aquila2009 database*

In this section, vulnerability curves for GD, R-GD and SD buildings will be derived. Vertical and horizontal types will be also considered. Generally speaking, vertical types are identified as bad quality/irregular layout and good quality/regular layout. The information about the presence of tie beams/tie roads, if any, is disregarded herein. Four horizontal types are identified: vaults (with or without ties), flexible-(i.e. wood), semirigid-(i.e. steel) and rigid-slab (i.e. RC).

Note that an acceptable sample size of 200 buildings is set in what follows (Rossetto et al., 2013) for deriving vulnerability curves. Thus, if the sample size of a given class is less than 200 buildings, the corresponding curve will not be derived and the dataset will be discarded.

Actually, the lack of some typologies has to be expected: for example, in case of GD buildings, the presence of RC slab is very unlikely (this kind of slab was recommended for the first time by R.D.25/03/1935 n.640, after Maiella 1933 earthquake). On the other hand, the recommendation made by D.M.L.L.P.P.2/07/1981 regarding the substitution of the original slab with a RC (or steel) slab can justify the presence of the typology for R-GD buildings.

Moreover, GD buildings characterized by good quality vertical structures are quite rare. Note that only after the R.D.18/04/1909 n.193, the use of pebbles and rubble masonry in construction for seismic areas is prohibited.

Vulnerability curves of Figure 3 show a clear hierarchy as a function of structural typologies, and given the latter as a function of vertical and horizontal types. As a matter of fact a decreasing vulnerability trend can be observed going from GD to R-GD buildings and from R-GD to SD ones. The effectiveness of retrofit intervention for bad quality/irregular layout buildings is highlighted by the fact that R-GD curves are very close to SD ones. On the other hand, the (small) difference between R-GD and SD curves, except in case of rigid slabs, highlights a reduced effectiveness for good quality/regular layout buildings.

Obviously, a decreasing vulnerability trend is observed increasing the masonry quality (from bad to good quality) and increasing the stiffness of horizontal structures (going from vaults to RC slabs), as shown in (Del Gaudio et al., 2019).

5.2 *Comparison of vulnerability curves between SD classes*

The information provided by Abruzzo 1984 survey form allows only to distinguish GD buildings from SD ones, without any further indication about the possible retrofit interventions made through the years.

In Figure 4, the comparison between the vulnerability curves for only SD buildings of L'Aquila 2009 and Abruzzo 1984 has been reported. A very good agreement between the curves for all the vertical and horizontal types can be observed.

Note that although all the buildings are located in Abruzzi Region, no overlapping area between the two databases is observed. Thus, there are not common terms between the lists of considered municipalities of the databases. However, the results in terms of vulnerability curves highlight the fact that probably the earthquakes occurred in those areas influence equally the professional practice for the considered design typology.

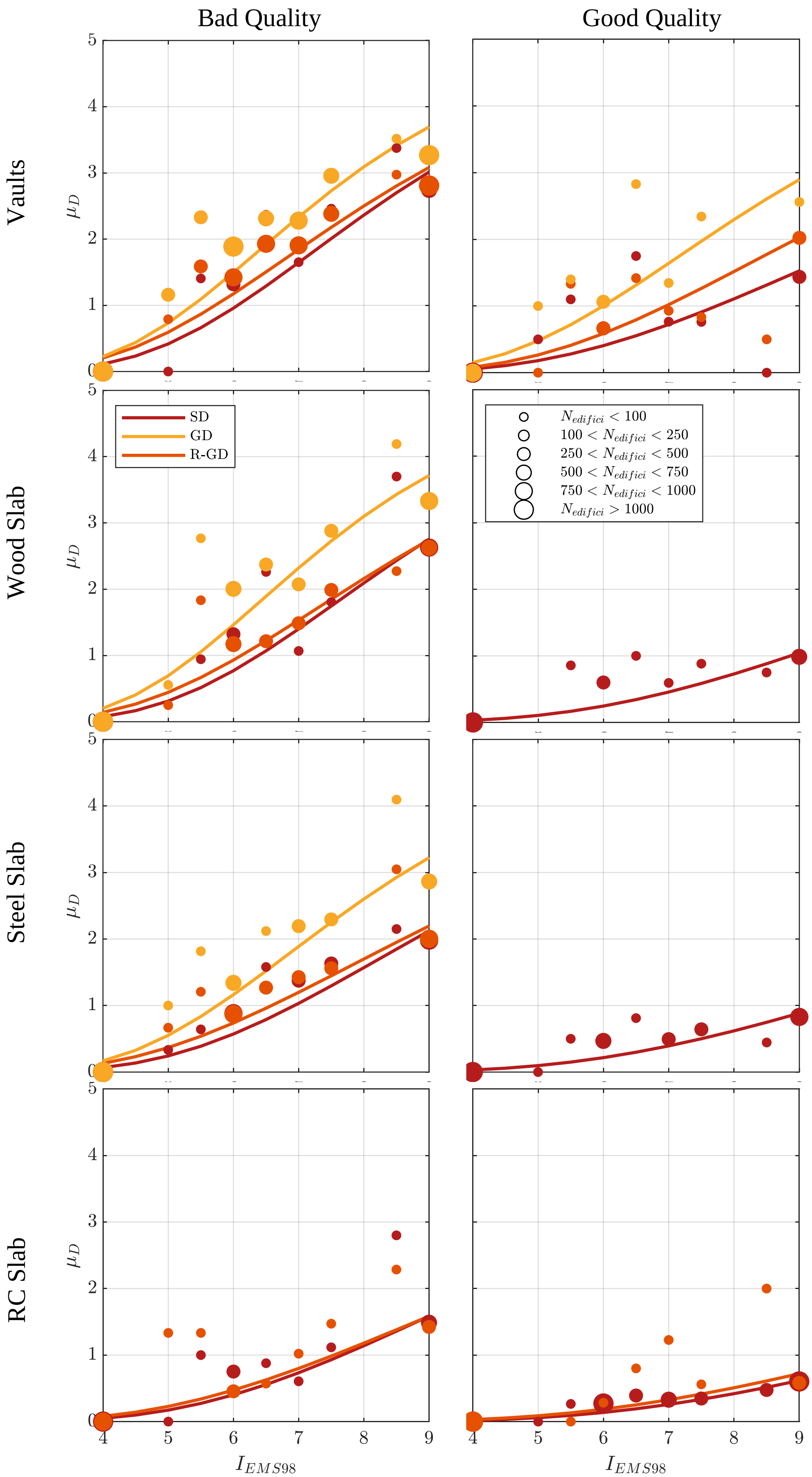

Figure 2. Vulnerability Curves for L'Aquila2009 database as a function of structural typology, vertical and horizontal types.

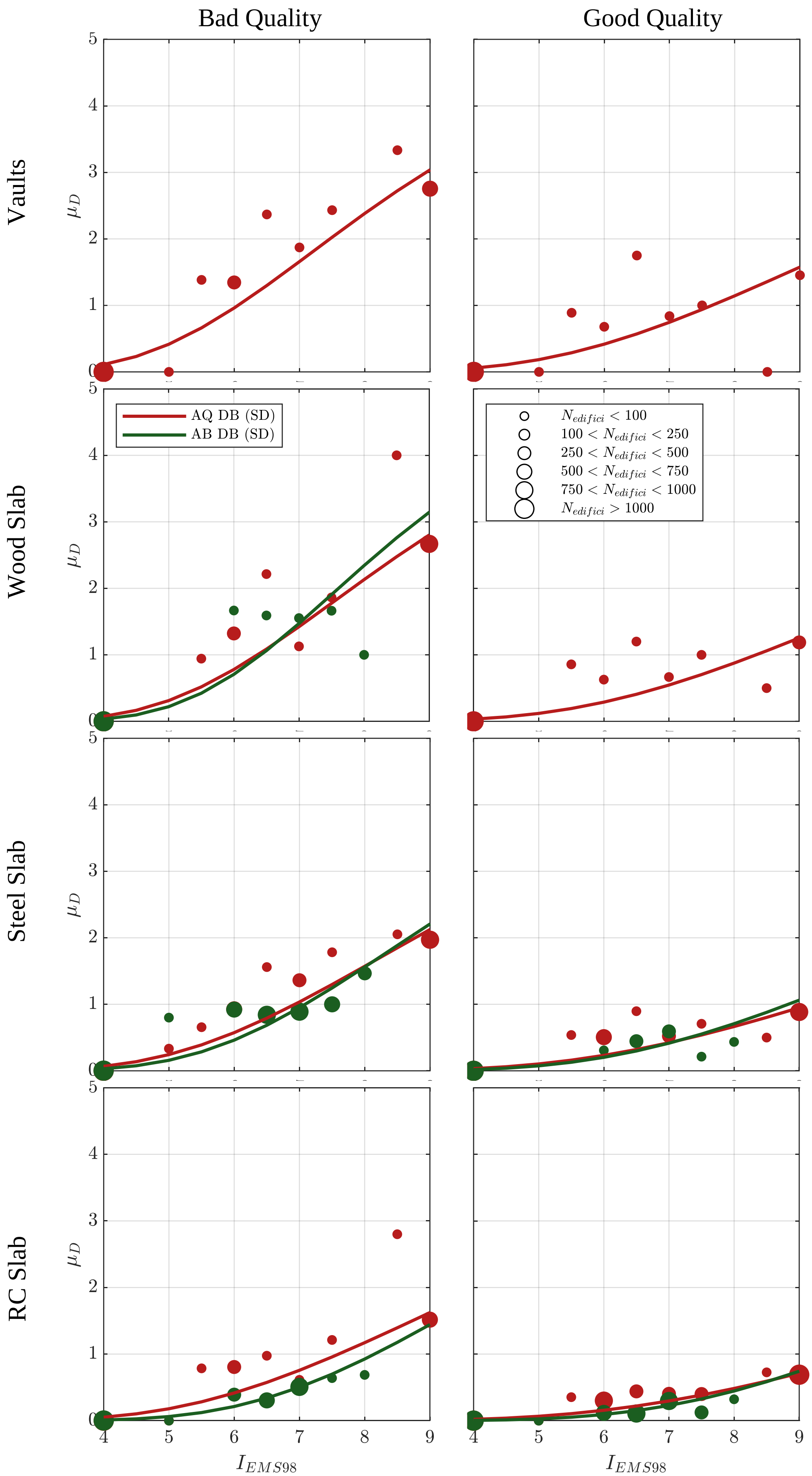

Figure 3. Comparison of vulnerability curves for SD buildings of L'Aquila2009 and Abruzzo1984 databases

5.3 Comparison between GD and R-GD classes

In this section, the comparison of GD and R-GD vulnerability curves for all considered databases will be shown (Figure 5). As previously stated, only for Molise 2002 and L'Aquila 2009 databases, information about the presence of retrofit intervention and its age are available (see Table 2).

Thus, for Irpinia 1980, Abruzzo 1984 and Umbria-Marche 1997 it is not possible to distinguish between GD and R-GD buildings, since the information is not explicitly reported in the survey form.

The comparison between GD and R-GD curves of Molise 2002 databases show the proximity between the aforementioned curves for all horizontal and vertical types, highlighting a limited effectiveness of the retrofit intervention. Note that great part of these Municipalities has been seismically classified with (OPCM 3274 20/03/2003). Thus, both the design and the retrofit, if any, should not take into consideration seismic loads but only gravitational ones.

Moreover, Figure 5 shows a quite good accordance of all the GD vulnerability curves with those of L'Aquila 2009 for bad quality masonry, except for Abruzzo 1984 database.

Generally speaking, GD buildings of Irpinia 1980 database could also contain some retrofitted buildings, since no information in this regard is reported in survey form. However, the proximity between these curves and the GD curves of L'Aquila 2009 database suggests that the retrofit interventions, if present, have a negligible influence similarly to the case of Molise 2002 database. In fact, being mostly classified after 1980, the potential retrofit intervention should not take into consideration seismic loads but only gravitational ones.

Conversely, GD curves for Abruzzo 1984 database result very close to R-GD curves of L'Aquila 2009 database, highlighting, on one hand, the presence of retrofitted buildings and, on the other hand, their effectiveness in vulnerability trends.

In conclusion, retrofit interventions appear to be more effective for seismically classified municipalities.

Lastly, the comparison between GD and R-GD vulnerability curves for good quality masonry are strongly affected by the reduced amount of data for all databases. Only Irpinia 1980 and Molise 2002 databases have a considerable number of buildings.

In particular, Irpinia 1980 and Molise 2002 vaulted buildings result in vulnerability not greater than those of L'Aquila 2009 considering only GD. Good-quality vaulted Irpinia 1980 buildings results overall more vulnerable of Molise 2002 ones. This difference gradually decreases for flexible and semi-rigid slabs and reverse for RC slabs, where Irpinia buildings result less vulnerable than Molise 2002 ones, but more vulnerable of R-GD buildings of L'Aquila 2009.

6 CONCLUSIONS

In this study, the evaluation of effectiveness of retrofit interventions on masonry buildings has been analyzed from the comparison of empirical vulnerability curves obtained from the data related to the major earthquakes occurred in Italy in the last 50 years (Friuli 1976; Irpinia 1980; Abruzzo 1984; Umbria-Marche 1997; Pollino 1998; Molise 2002; Emilia 2003; L'Aquila 2009; Emilia 2012).

Vulnerability curves have been derived considering Macro-seismic intensity values, obtained for each Municipality from (Rovida et al., 2016). Mean damage values for each building has been evaluated considering 5+1 damage levels defined according to European Macro-seismic Scale EMS-98 (Grünthal, 1998) from observed damage for vertical structures collected during the inspections.

The considered building dataset has been divided as a function of structural typologies (seismic or gravitational), the presence of retrofit interventions, horizontal and vertical types. Thus, three structural typologies have been considered, namely gravity load designed buildings (GD), seismic load designed buildings (SD), gravity load designed buildings subjected to subsequent retrofit interventions (R-GD), together with all possible combinations between vertical and horizontal types.

For what concern seismic load design buildings, the comparison between L'Aquila 2009 and Abruzzo 1984 databases showed a very good agreement between the curves for all vertical and horizontal types. This result can be addressed with the fact that the earthquakes occurred in Abruzzi region probably have influenced equally the professional practice, being equal their design typology.

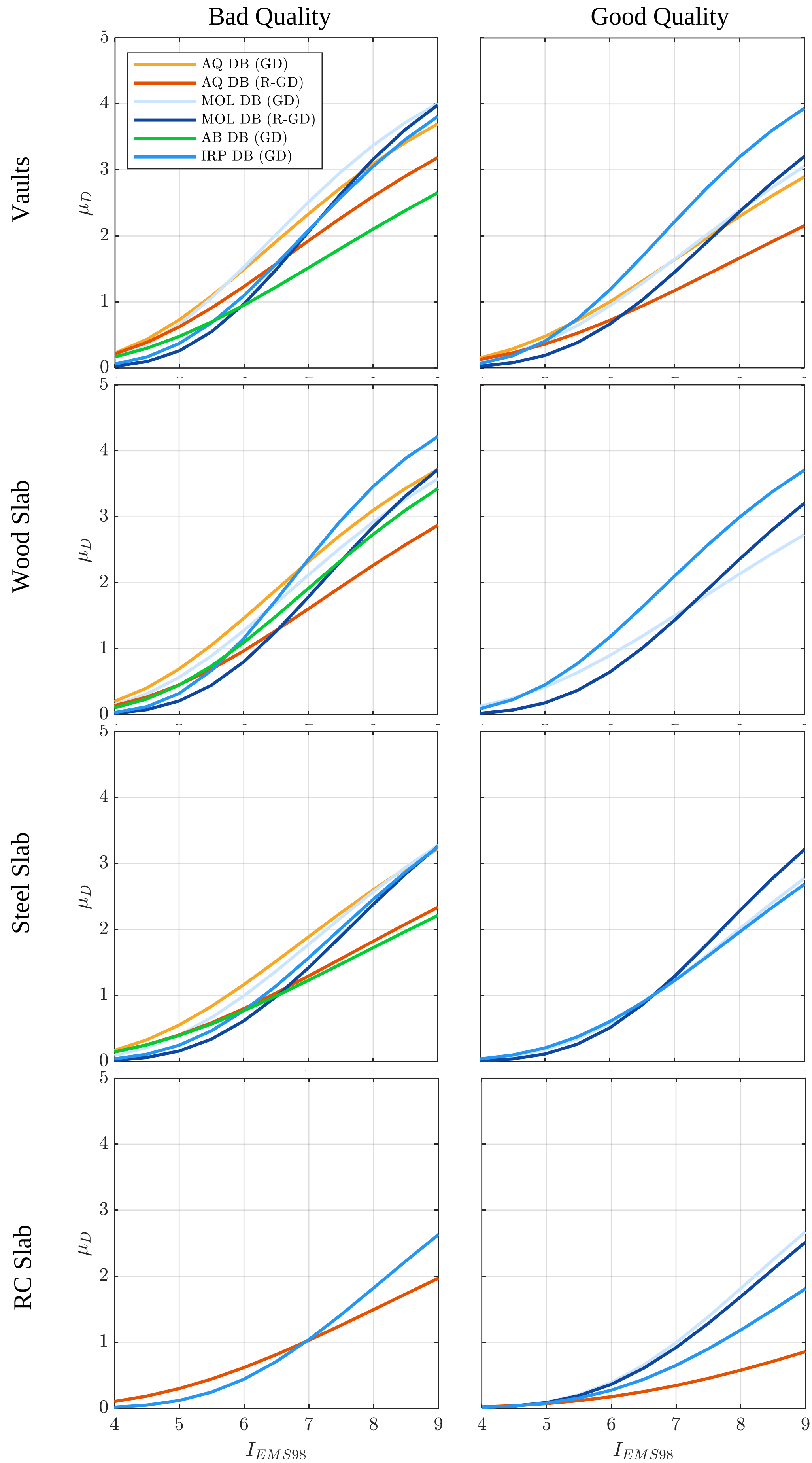

Figure 4. Comparison of vulnerability curves for GD and R-GD buildings of all databases as a function of vertical and horizontal types

L'Aquila 2009 and Molise 2002 databases allow a direct comparison between gravity load designed buildings (GD) and retrofitted ones (R-GD), being this information directly available from the survey form. The comparison between the curves highlights that the effectiveness of retrofit intervention for bad quality/irregular layout buildings can be proven only for seismically classified Municipalities.

This trend is indirectly confirmed also from Irpinia 1980 and Abruzzo 1984 databases. Although no information is available from the survey campaign, the proximity of vulnerability curves of Irpinia 1980 with L'Aquila 2009 for GD structural typology and those of Abruzzo 1984 with L'Aquila 2009 for R-GD structural typology, confirms the effectiveness of retrofit interventions only in area seismically classified.

Conversely, vulnerability curves for good quality masonry are strongly affected by the reduced amount of data for all databases. Then, for this type, further insights are needed.

REFERENCES

Baggio, C., Bernardini, A., Colozza, R., Corazza, L., Della Bella, M., Di Pasquale, G., Papa, F., 2007. *Field manual for post-earthquake damage and safety assessment and short term countermeasures (AeDES).* European Commission—Joint Research Centre—Institute for the Protection and Security of the Citizen, EUR, 22868.

Braga F., Dolce M., Liberatore D., 1982. *A statistical study on damaged buildings and an ensuing review of the MSK-76 scale.* Proceedings of the seventh European conference on earthquake engineering, Athens, Greece, 431-450.

Colombi M., Borzi B., Crowley H., Onida M., Meroni F., & Pinho R., 2008. *Deriving vulnerability curves using Italian earthquake damage data*. Bulletin of Earthquake Engineering, 6(3), 485-504.

D'Ayala D. F., Paganoni S., 2011. *Assessment and analysis of damage in L'Aquila historic city centre after 6th April 2009*. Bulletin of Earthquake Engineering, 9(1), 81-104.

Del Gaudio C., Ricci P., Verderame G.M., 2015. *ECS-it – Evoluzione della classificazione si-smica in Italia*. ReLUIS, Naples, Italy. Available at http://www.reluis.it/

Del Gaudio C., De Martino G., Di Ludovico M., Manfredi G., Prota A., Ricci P., Verderame G.M., 2019. *Empirical fragility curves for masonry buildings after the 2009 L'Aquila, Italy, earthquake.* Bulletin of Earthquake Engineering https://doi.org/10.1007/s10518-019-00683-4.

Dolce M., Goretti A., 2015. *Building damage assessment after the 2009 Abruzzi earthquake*. Bulletin of Earthquake Engineering, 2241-2264. DOI 10.1007/s10518-015-9723-4.

Goretti A., Di Pasquale G., 2004. *Building inspection and damage data for the 2002 Molise, Italy, earthquake.* Earthquake Spectra, S167-S190. DOI: 10.1193/1.1769373.

Grünthal M., 1998. *European Macro-seismic Scale.* Cahiers du Centre Européen de Géodynamique et de Séismologie, Vol. 15. European Macro-seismic Scale 1998. European Center for Geodynamics and Seismology.

Rossetto T., Ioannou I., Grant D.N., 2013. *Existing empirical fragility and vulnerability functions: Compendium and guide for selection*, GEM Technical Report 2013-X, GEM Foundation, Pavia, Italy.

Rota M., Penna A., Strobbia C.L., 2008. *Processing italian damage data to derive typological fragility curves*. Soil Dynamics and Earthquake Engineering, 933-947.

Rovida A., Locati M., Camassi R., Lolli B., Gasperini P. (eds), 2016. *CPTI15, the 2015 version of the Parametric Catalogue of Italian Earthquakes*. Istituto Nazionale di Geofisica e Vulcanologia. doi:http://doi.org/10.6092/INGV.IT - CPTI15

Sabetta F., Goretti A., Lucantoni A., 1998. *Empirical Fragility Curves from Damage Surveys and Estimated*. 11th European Conference on Earthquake Engineering © 1998 Balkema, Rotterdam, ISBN 90 5410 982 3.

Sisti R., Di Ludovico M., Borri A., Prota A., 2018. *Damage assessment and the effectiveness of prevention: the response of ordinary unreinforced masonry buildings in Norcia during the Central Italy 2016–2017 seismic sequence*. Bulletin of Earthquake Engineering, 1-21. https://doi.org/10.1007/s10518-018-0448-z

Zucconi M., Ferlito R., Sorrentino L., 2018. *Simplified survey form of unreinforced masonry buildings calibrated on data from the 2009 L'Aquila earthquake*. Bulletin of Earthquake Engineering, 16(7), 2877-2911.