Empirical vulnerability curves for Italian mansory buildings: evolution of vulnerability model from the DPM to curves as a function of accelertion

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EMPIRICAL VULNERABILITY CURVES FOR ITALIAN MASONRY BUILDINGS

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Abstract

In the seismic risk assessment, the factor concerning the vulnerability of buildings under effect of earthquakes assumes a crucial importance. The research aims to evaluate vulnerability curves for masonry Italian buildings through a critical observational approach, useful for analyses at national scale.
To this purpose, a damage and typological Italian database is exploited and, on the basis of its contents statistical correlations among level of damage, hazard input and typological characteristics of the buildings are studied. The vulnerability curves are derived using a regression method and their calibration is supported by critical observations on the reliability of the dataset and, consequently, by introducing corrective hypotheses.
Furthermore, the research proposes a validation of the curves through the IRMA platform (Italian Risk MAp), a tool developed by Italian Civil Protection for the development of analysis of scenario and risk.

Keywords: Seismic risk assessment, empirical approach, masonry buildings.

1 INTRODUCTION

In the framework of disaster risk reduction, the "risk assessment" phase assumes a crucial role. The evaluation of damage induced by seismic events on the elements exposed constitute the first step to achieve a high level of protection of hit territory.

The “risk” is the probability to reach a predetermined level of damage on given element exposed (people, buildings, infrastructures, economy, etc.) caused by seismic events occurring in a given period of time and in a certain geographical area. The risk should be considered as a cumulative assessment, related to the potential total damage generated by all seismic events that can occur in a given area in a predetermined period of time. The “scenario”, instead, represents the probabilistic distribution of the damage, in a given geographical area, caused by a single seismic event of intensity “i” (chosen as "reference scenario"), with assigned probability of occurrence [1]. In both analyses, three aleatory variables (hazard, exposure and vulnerability) must be considered according to the convolution (1).

$$\text{Risk [Scenario]} = \text{Hazard Scenario [Single Hazard]} \times \text{Exposure} \times \text{Vulnerability} \qquad (1)$$

The “hazard scenario” is the probability of occurrence of all the possible seismic events [of each single “hazard” event] in a specific area during a specific time. The “exposure” is the qualitative and quantitative geographic distribution of the different elements at risk (population, buildings, infrastructures, activities and facilities) which characterize the examined area, whose conditions and/or functionality could be damaged, modified and destroyed because of the occurrence of the seismic events. The “vulnerability” is the response of an exposed element at risk to a given seismic event. It can be assessed as the probability that an exposed element at risk reaches a given level of damage, according to an opportune measurement scale, under the effects of a natural event of assigned intensity.

In this paper, seismic vulnerability for Italian masonry buildings is evaluated. Seismic buildings vulnerability can be essentially evaluated exploiting three methods [2]: empirical approach, analytic approach and hybrid approach. The first one provides to define buildings behavior exploiting detected data about structures affected by seismic events. In particular, statistical correlation and regression methods are used to define the relation among typological characteristics of the buildings, hazard input and level of damage. The second one studies buildings vulnerability through mechanical analyses able to describe the damage evolution of a building with assigned typological and structural characteristics, increasing the hazard input value. In the third the vulnerability curves are obtained combining the mechanical and observational analyses of the damages produced by past events.

The research proposed adopts a critical empirical approach based on the statistical analyses of damaged observe on Italian masonry buildings after past seismic events aiming to develop "vulnerability curves".

The seismic vulnerability of buildings by empirical approach can be assessed by two main tools: the damage probability matrices DPM, which express in a discrete form the conditional probability of obtaining a damage level j, due to a ground motion of intensity i; and the vulnerability functions, which are continuous functions expressing the probability of exceeding a given damage state, given a function of the earthquake intensity.

The initial obstacle to derivation of continuous vulnerability functions, compared to DPM, is due to discrete scale of the macroseismic intensity. The problem has been overcome by using Parameterless Scale of Intensity, PSI ([3], [4]), subsequently converted to PGA using empirical correlation functions.

In the literature, vulnerability curves have been derived as binomial [5], normal or lognormal distributions ([6], [7]) as a function of PGA or also connected to spectral acceleration or spectral displacement at the fundamental elastic period of vibration ([8], [9], [10]).

The approach described aims to assess vulnerability curves, as a lognormal distribution in function of PGA, for Italian masonry buildings. To this purpose, a damage and typological Italian database is exploited and, on the basis of statistical correlations damage-motion relationships are studied. The vulnerability curves are derived using a regression method and their calibration is supported by critical observations on the reliability of the dataset and, consequently, by introducing corrective hypotheses.

As all empirical approaches, the study assumes that damage due to past earthquakes observed in the structures classified by type, will be the same in future earthquakes in that region and it will be representative of the vulnerability for areas with similar building stocks when subjected to similar size future events. The reliability of this curves, in the framework of Italian risk assessment, at national scale, is connected to the large size of database (about 240,000 buildings), which can well reflect the real damage and incorporates the effects on building response of factor such as material degradation, configuration and detailing arrangement, which are otherwise difficult to model.

The curves are developed in the framework of the technical board promoted by Italian Civil Protection with the aim to develop seismic vulnerability curves for Italian buildings differently classified in function of vertical structures (masonry and reinforced concrete) to assess scenario and risk analyses by IRMA platform, Italian Risk MAp [11].

2 CALIBRATION

The steps adopted to calibrate the vulnerability curves exploiting the PLINIVS damage database are:

- Uniformity of the database;
- Assignment of the class for each building in the database
- Mathematical calibration of the vulnerability curves.

In particular, the last step is done exploiting the procedure illustrated in Figure 1. In this work, only the optimal hypothesis on the not detected data is reported, and criteria for the validation are illustrated in Paragraph 3.

2.1 Uniformity of the database

The PLINIVS database contains information on approximately 240,000 masonry buildings. The database is constituted by data collected for main Italian seismic events (Irpinia 1980, Umbria Marche 1997, Molise Puglia 1997, Pollino 1998, Emilia 2003, Aquila 2009, Emilia 2012). Each survey activity is related to a different form that differently organizes information about typological characteristics and level of damage. In particular, Irpinia 1980 is surveyed with Irpinia form and the others seismic events are surveyed with AeDES form. A uniformity of the database is done by choosing the most important typological and structural characteristics in the forms and by defining the possibilities of each characteristic. The chosen parameters and their classes are reported in Table 1.

Furthermore, an adaptation at the same scale of the different ranges of the levels of damage is done. In particular, the six levels of damage of the EMS98 are used as reference of the proposed model: D0: no damage; D1: not structural damage; D2: light structural damage; D3: structural damage; D4: partial collapse; D5: total collapse. An adaptation of the forms range to this scale is summarized in Table 2.

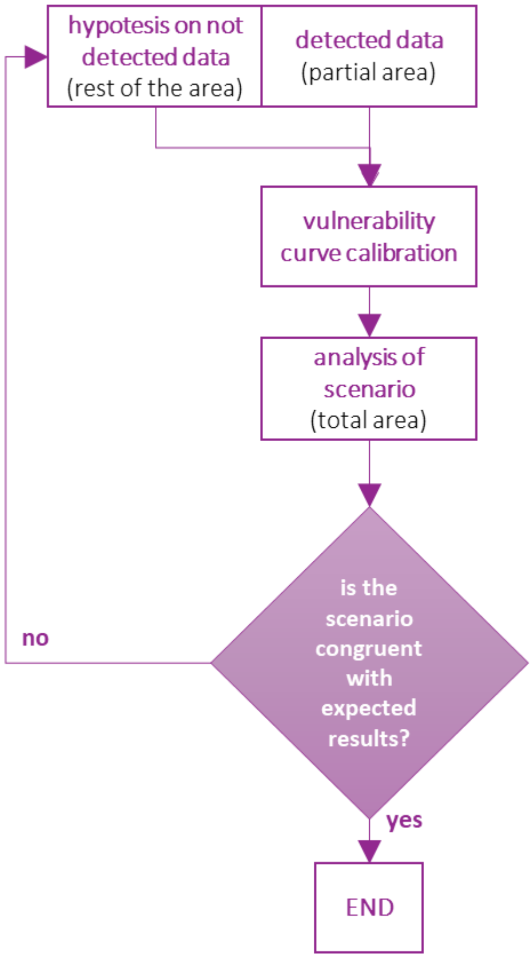


Figure 1: synthetic diagram of the adopted procedure

2.2 Assignment of the vulnerability class for each building of the database

The definition of the behavior of a building based on its structural typological characteristics is evaluated using the "S.A.V.E." method [12], a procedure for a quick assignment of the seismic vulnerability according to the classification adopted in EMS'98. The assignment criterion adopted by the EMS98 is essentially based on the characteristics of the vertical structure, with uncertainty intervals in some rather large cases (Figure 2). These uncertainty intervals can also significantly influence risk or impact analyses. "S.A.V.E." method starts from the same concept of the EMS'98 and defines the average behavior of a building considering its vertical structure. In a second step reduces the uncertainty in the assessment of the vulnerability class through the systematic observation of others typological and structural characteristics of the building influencing the response. These are associated to numerical parameters that represent the vulnerability level modifiers, applied within a rapid vulnerability estimation algorithm. Numerically, the weight of each of these parameters is evaluated through the statistical analysis on the PLINIVS database of typological recurrences and seismic damage recorded during past earthquakes.

PARAMETERS	**VARIABLE OF THE PARAMETER** 1	2	3	4	5	6
Vertical structure	generic masonry	weak and irregular masonry	regular and good quality masonry			
Horizontal Structure	wooden floor	steel floor	brick cement floor	vault	mixed	
Number of floors	1-2	3-4	5-6	7-8	more of 8	
Age of construction	< 1919	1919-1945	1946-1961	1962-1971	1972-1981	>1981
Position in the aggregate	isolated	lateral	center	corner		
Isolated columns	yes	no				
Horizontal connections	yes	no				
Plant regolarity	yes	no				
Infill regolarity	yes	no				
Roof	light	heavy	light with thrust	heavy with thrust	light without thrust	heavy without thrust
Structural reinforcement	no reinforce	steel reinforce	no steel reinforce	other		

Table 1: considered parameters and their variables

IRPINIA FORM			
Level of damage of Vertical Structure	**Convertion in EMS'98 scale**	**Level of damage of Horizontal Structure**	**Convertion in EMS'98 scale**
0	0	**0**	0
1		**1**	
2	1	**2**	1
3	2	**3**	2
4	3	**4**	
5		**5**	3
6	4	**6**	4
7		**7**	
8	5	**8**	5

(a)

AeDES FORM			
Level of damage of Vertical Structure	**Convertion in EMS'98 scale**	**Level of damage of Horizontal Structure**	**Convertion in EMS'98 scale**
L	0	L	0
H	2	H	1
I		I	2
G	3	G	
F		F	3
E		E	
D		D	
C	4	C	4
B	5	B	
A		A	5

(b)

Table 2. Conversion of level of damage into the EMS'98 range of damage for Irpinia Form (a) and AeDES Form (b)

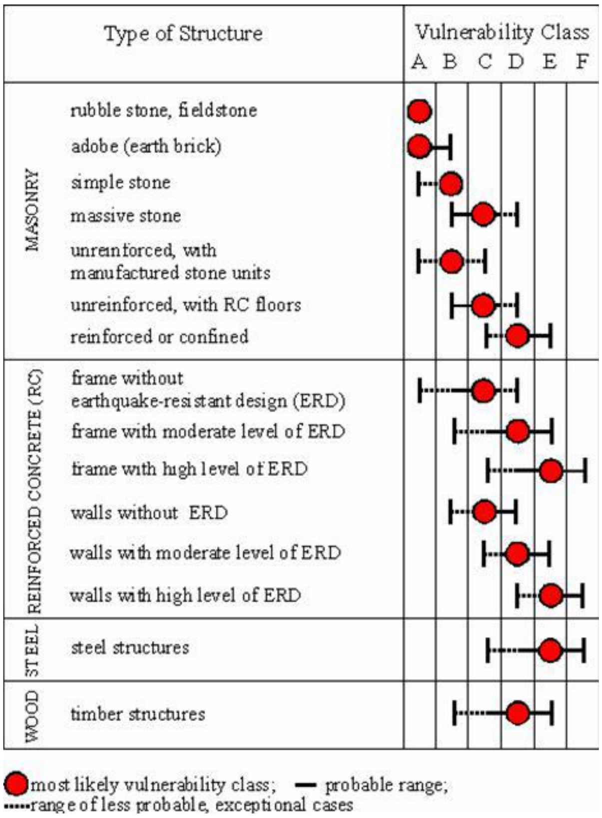


Figure 2. EMS'98 vulnerability classes and uncertainly ranges

The “S.A.V.E”. method proposes the definition of vulnerability classes on the basis of the vertical structure behavior. In particular, three classes of Vertical Structure (VS) are defined as below:

- V0- "Generic" masonry (in the absence of information on the quality of the wall structure)
- V1 - Weak and irregular masonry.
- V2 - Regular and good quality masonry

Each building in the database is assigned the corresponding Vi class. The response of buildings grouped by class is examined for each level of seismic intensity and damage distributions are defined (D0, D1, ... D5). For each of the three VS damage distributions the Synthetic Damage Parameter (SPD_{Vi}) is estimated, identifying it as the barycentric abscissa of the damage distribution. On the basis of this analysis, three ranges of SPD representative of the VS are evaluated. In particular, Class A represents the weak and irregular masonry, class B the “Generic” masonry and class C1 the regular and good quality masonry (Table 3).

	A	**B**	**C1**
$SPD_{V,max}$	5.00	2.20	1.60
$SPD_{V,min}$	2.20	1.60	0.00

Table 3: range of SPD_V for each vulnerability class

Parameters summarized in Table 1 are considered as the modifier that can improve or worsen the average behavior of a building under seismic action and, consequently, influence the assignment of the vulnerability class. With the aim of evaluating their influence, the $SPD_{Vi\text{-}Pjk}$ is estimated on the sample of buildings with a chosen VS and the considered parameter. For example, with the purpose to evaluate the influence of the horizontal structure on "Generic" masonry (V0) buildings, $SPD_{V0\text{-}Pjk}$ value is calculated for V0 with wooden floor sample, V0 with steel floor sample, etc. The difference between $SPD_{Vi\text{-}Pik}$ value and the SPD_{Vi} value defines the influence of the modifier *k* of the parameter Pj in the vertical structure Vi. At the end, for each building, assumed as the "base" score the average SPD_{Vi} value of the class VS belonging to, the vulnerability score is calculated by adding to it the contributions of all the known parameters by the following equation (1):

$$SPD = SPDv + \sum_{s=1}^{n} q_s + \frac{\sum_{j=1}^{m}\sum_{i=1}^{m}(p_j + p_i)c_{ij}}{2m} \quad (1)$$

in which:

- q is the influence of the independent parameter
- p is the influence of the dependent parameter
- n is the number of independent parameters
- m is the number of dependent parameters
- c_{ij} is che coefficient of correlation between pi and pj parameters (see [12] to depeen)

2.3 Mathematical calibration of the vulnerability curves

The vulnerability curve represents the probability that a level of damage is reached or exceeded for a fixed value of hazard. In this work the vulnerability curves are obtained applying the minimum square regression method on the data derived by the database. In particular, for each vulnerability class the buildings distribution on each hazard value is estimated, and the cumulative values of each level of damage are calculated and regression method is applied on the results. The hazard values associated to each municipality in the database is in intensity, and a conversion in PGA is engineeringally convenient. To this purpose, the Margottini [13] law conversion, equation (2), is applied.

$$a = \frac{10^{(0{,}525+0{,}22\ i)}}{981} \quad (2)$$

The accuracy of the buildings distribution for each considered hazard value represents a fundamental requirement for the right calibration of the curves. The accuracy depends on the completeness of the dataset index Ic, defined as the percentage of surveyed buildings compared to the total buildings on the area invested by the considered hazard. The assumption of the buildings distribution evaluated on the database represents a generalization of the obtained values on the total area invested by the considered hazard. So, the reliability of the values is strictly related to the percentage of surveyed buildings: a high percentage gives a more accuracy value. The regression used to calibrate the vulnerability curves takes in account the reliability of the data exploiting the completeness of the sample. In particular, for each hazard value the completeness index Ic is evaluated, and it's also used as weight of the associated buildings distribution.

The evaluation of the completeness index Ic to be associated to the hazard values is done exploiting the seismic event of Aquila2009 only, because of its good completeness of data. Required information are: the hazard input, the total number of buildings in the affected area and the number of detected buildings. The hazard input is derived by shakemap furnished by the INGV, in which the peak ground acceleration values are furnished through isoacceleration curves with steps of 0,02g. The total number of buildings in the affected area is derived by the ISTAT2001, in which the total number of buildings is furnished for unit zones. The number of detected buildings is provided by the PLINIVS database for each municipality. Since the inventory of building stored in the PLINIVS database is grouped by municipalities, in order to harmonize the information, the ISTAT2001 data, provided by census zones, have to be converted and grouped by single municipalities. A single value of PGA is associated to each municipality. In particular, the value is obtained considering the PGA value of the L'Aquila 2009 shakemap, represented in Figure 3, corresponding to the centroid of the municipality.

For each step value of PGA all associated municipalities are considered, and the numbers of detected buildings and the total present buildings are evaluated. At the end, the completeness index Ic for each PGA value is estimated as ratio of detected buildings and total buildings. In Figure 3 are also highlighted municipalities with Ic ≥ 30%. The completeness index Ic obtained on the L'Aquila2009 sample represents the best calibration that can be done since the good completeness of the sample, so a generalization of the calculated correspondence Ic – PGA of this sample is done for all the database.

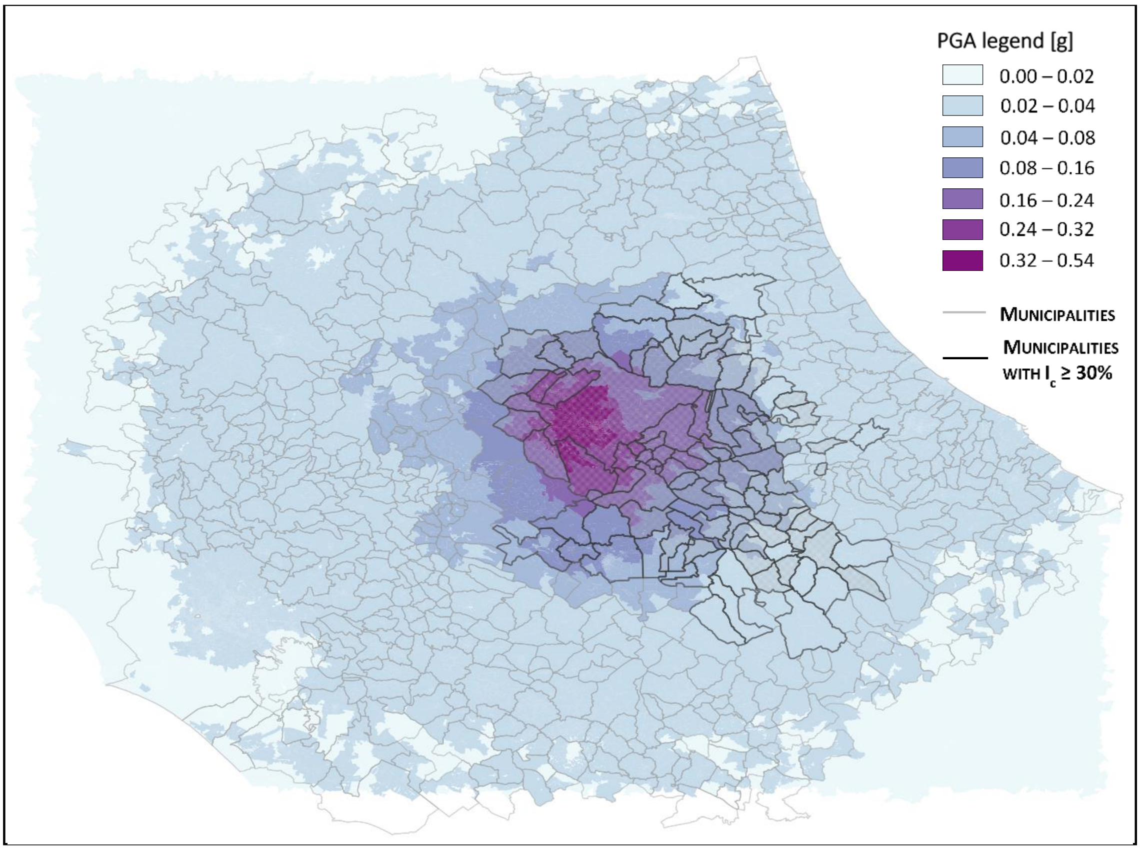


Figure 3. L'Aquila2009 shakemap

In Table 4 the cumulative damage building distribution and the completeness index Ic associated to each PGA value are resumed for each vulnerability class and each level of damage. Results in Table 4 show that at lower values of hazard corresponds lower values of Ic. The reasons are essentially two: the first one is that at lower hazard values corresponds larges areas, the second one is that a lower hazard generates less damages therefore there is a high probability that no damaged buildings are neglected. "No information" at lower hazard values

		CLASS A					CLASS B					CLASS C1				
PGA	**Ic**	**D1**	**D2**	**D3**	**D4**	**D5**	**D1**	**D2**	**D3**	**D4**	**D5**	**D1**	**D2**	**D3**	**D4**	**D5**
0,04	4%	0,80	0,43	0,27	0,12	0,03	0,70	0,26	0,12	0,04	0,01	0,59	0,12	0,05	0,02	0,00
0,08	12%	0,81	0,55	0,30	0,13	0,03	0,62	0,34	0,10	0,03	0,01	0,43	0,12	0,04	0,01	0,00
0,12	46%	0,85	0,67	0,39	0,22	0,04	0,62	0,41	0,15	0,08	0,02	0,45	0,18	0,05	0,02	0,00
0,16	38%	0,92	0,76	0,49	0,31	0,06	0,82	0,56	0,27	0,13	0,02	0,65	0,27	0,06	0,03	0,01
0,20	45%	0,91	0,74	0,44	0,25	0,06	0,71	0,47	0,19	0,09	0,01	0,54	0,22	0,08	0,03	0,00
0,24	39%	0,82	0,59	0,42	0,22	0,06	0,66	0,34	0,18	0,07	0,01	0,41	0,11	0,04	0,01	0,00
0,28	62%	0,84	0,61	0,48	0,28	0,09	0,71	0,35	0,22	0,11	0,04	0,46	0,09	0,04	0,02	0,00
0,32	84%	0,94	0,83	0,55	0,37	0,11	0,85	0,67	0,35	0,21	0,05	0,60	0,37	0,15	0,06	0,02
0,36	100%	0,87	0,71	0,59	0,41	0,16	0,72	0,47	0,35	0,21	0,08	0,61	0,29	0,13	0,06	0,01
0,54	100%	0,98	0,92	0,76	0,63	0,33	0,77	0,54	0,26	0,16	0,05	0,83	0,56	0,15	0,04	0,01

Table 4. Cumulative damage percentage values for each level of damage and each vulnerability class

can be considered as a “no necessary information” for the surveyors, i.e. absence of damage. The map in Figure 3 shows that for PGA ≤ 0,02 g there are no information, so there is a high probability that the buildings are not damaged. The reasonable hypothesis that there are no damaged buildings for each vulnerability class with PGA = 0,02 g is taken into account. Furthermore, considering the high probability of the accuracy of this hypothesis, a completeness index Ic = 0,95 is associated to this PGA value.

Furthermore, another conceptual assumption is done. Vulnerability curves representative of different levels of damage but belonging to the same class can’t have intersection points. To avoid mathematically this problem, the same logarithmic standard deviation is assumed for curves of the same vulnerability class.
At the end, exploiting the minimum square regression method, curves are derived by equations (3):

$$\text{find}(\lambda,\beta):\ \min\{Ic_i[y_i - \log(x_i,\lambda,\beta)]^2\} \tag{3}$$

in which

- x_i is the PGA value;
- y_i is the cumulative distribution of the considered damage associated to the x_i value;
- Ic_i is the completeness index associated to the x_i value;
- λ is the logarithmic mean of the curve;
- β is the logarithmic standard deviation of the curve.

The obtained curves are represented in Figure 4.

3 VALIDATION

A validation of the vulnerability curves calibrated into the Paragraph 2 is done on the L’Aquila2009 scenario through the IRMA (Italian Risk MAp) platform, a tool developed by Italian Civil Protection with the aim of evaluate casualties caused by expected Italian seismic events in a fixed time window. The platform is also able to evaluate the consequences of past Italian seismic events such as L’Aquila2009. One of the strength points of the platform is the possibility to analyze separately the sample of buildings in reinforced concrete and the masonry one. In this work, only vulnerability curves for masonry buildings are calibrated so only this sample is considered in the platform.
Two kinds of data are in the platform: 1) not accessible and not editable data and 2) data set by the user. In the first group of data there are the input hazard values and the disaggregated ISTAT2001 database.

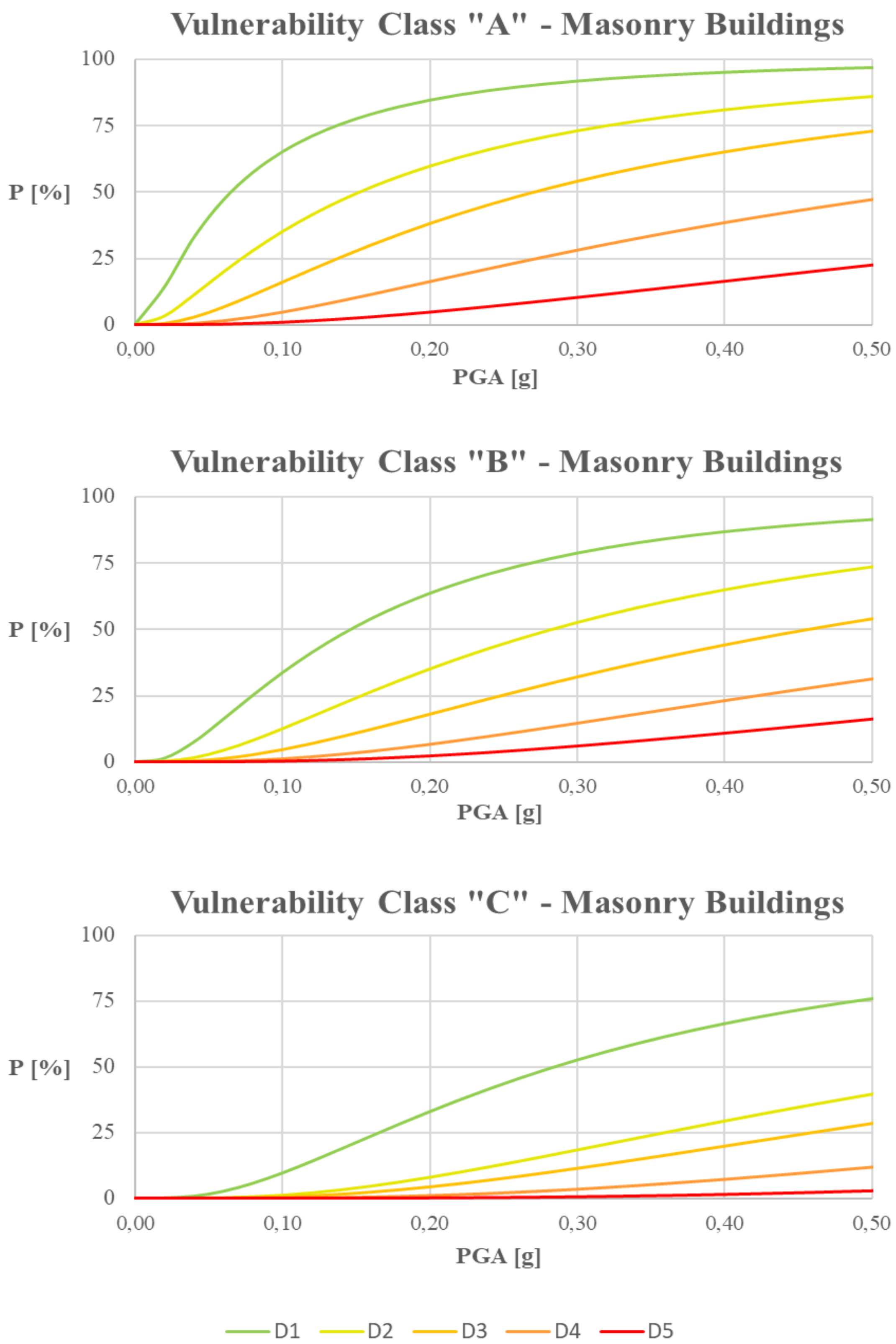


Figure 4. Vulnerability curves obtained by the regression method

Input hazard is in PGA and it's derived by a shakemap for the scenario assessment and by probability functions for risk maps analyses. Disaggregated ISTAT2001 database allows to evaluate the exposure on the areas exploiting some user input data.
In the second group of data there are the parameters of the vulnerability curves and the buildings distribution on the vulnerability classes for the combination of group of floors and age of building. Required parameters of the vulnerability curves are mean μ and standard deviation σ of the functions for each combination of vulnerability class and group of floors. The parameters are obtained by logarithmic mean λ and logarithmic standard deviation β calibrated into the regression method exploiting the equations (4):

$$\mu = e^{(\lambda + 0.5\beta^2)}$$
$$\sigma = \sqrt{\mu^2 (e^{(\beta^2)} - 1)} \quad (4)$$

At the end, keeping in mind that the proposed method does not furnished differentiated parameters for the combination vulnerability class / group of floors, the updated mean and standard deviation in the platform depending on the vulnerability class only are summarized in Table 5 and buildings distribution in the vulnerability classes in summarized in Table 6.

	D1		**D2**		**D3**		**D4**		**D5**	
	μ	**σ**	**μ**	**σ**	**μ**	**σ**	**μ**	**σ**	**μ**	**σ**
A	0,120	0,184	0,280	0,429	0,446	0,584	0,882	1,157	1,760	2,307
B	0,220	0,245	0,424	0,473	0,684	0,764	1,162	1,298	1,828	2,042
C1	0,393	0,372	0,850	0,804	1,085	1,028	1,776	1,682	3,124	2,958

Table 5. mean and standard deviation of vulnerability curves

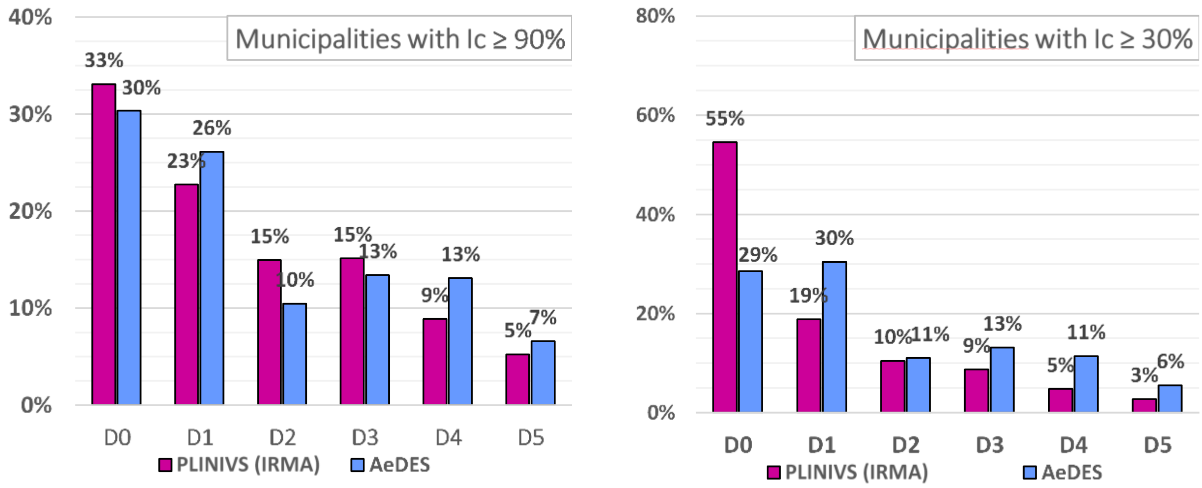
On the basis of this values, L'Aquila2009 scenario is calculated on the platform and buildings distribution on the six levels of damage is derived for municipalities with Ic ≥ 30% and Ic ≥ 90%. A comparison with the buildings distribution furnished by the database (derived by the AeDES forms) in the same municipalities is presented in Figure 5.
Figure 5.a shows a good approximation between buildings damage distribution derived by vulnerability curves presented in the paper and damage buildings distribution derived by PLINIVS database processed by AeDES. The higher difference of buildings percentage is, in fact, equal to 5% for the level of damage D2. Figure 5.b, contrary, shows that vulnerability curves return a higher percentage of not damaged buildings (level of damage D0). The obtained results are congruent with observation done in paragraph 2: low values of Ic are caused by no detection of not damaged buildings.

4 CONCLUSIONS

The proposed research aims to evaluate vulnerability curves, as a lognormal distribution in function of PGA, for masonry Italian buildings through a critical observational approach. To this purpose the PLINIVS is exploited, and on the basis of these contents statistical correla-

Age of construction	group of floors	Class A	Class B	Class C1
	1-2	70%	27%	3%
< 1919	3-4	73%	24%	3%
	5 or more	80%	12%	8%
	1-2	55%	36%	9%
1919 - 1945	3-4	60%	30%	10%
	5 or more	30%	20%	50%
	1-2	32%	51%	17%
1946-1961	3-4	39%	31%	30%
	5 or more	1%	21%	78%
	1-2	18%	55%	27%
1962-1671	3-4	28%	25%	47%
	5 or more	19%	8%	73%
	1-2	13%	48%	39%
1972 - 1981	3-4	27%	20%	53%
	5 or more	11%	6%	83%
	1-2	14%	16%	70%
> 1982	3-4	20%	16%	64%
	5 or more	20%	1%	79%

Table 6. Buildings distribution on the vulnerability class depending on age of construction and group of floors



(a) (b)

Figure 5. damage buildings distribution derived by vulnerability curves [PLINIVS (IRMA)] and PLINIVS database (AeDES)

tions among level of damage, hazard input and typological characteristics of the buildings are studied. The vulnerability curves are derived exploiting a regression method, and their calibration is supported by critical observations on the reliability of the dataset and, consequently, by introducing corrective hypotheses. The reliability of this curves, in the framework of Italian risk assessment, at national scale, is founded to the large size of database (about 240,000 buildings), which can well reflect the real damage and incorporates the effects on building response of factor such as material degradation, configuration and detailing arrangement, which are otherwise difficult to model.

As all the empirical method, this study has the limit that assumes that damage due to past earthquakes observed in the structures classified by type, will be the same in future earthquakes in that region and it will be representative of the vulnerability for areas with similar building stocks when subjected to similar size future events. However, differently to the analytic method it has the advantage that takes in account the true state of deterioration of the building without introducing hypothesis in the modeling.
In this work a validation of the curves is proposed in reference to L'Aquila2009 earthquake, that is a part of the sample used to calibrate the curves, so a partial self-reference has to be taken into account. Future developments plan to adopt the vulnerability curves developed with reference to seismic events not used for the calibration of the vulnerability curves. The aims of these developments are the exhaustive evaluation of the reliability of the vulnerability curves and the determination of the representativeness of the Aquila area on different Italian areas.

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