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DERIVATION OF MECHANICAL FRAGILITY CURVES FOR MACRO-TYPOLOGIES OF ITALIAN MASONRY BUILDINGS

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Abstract

Seismic risk mitigation at national scale requires the vulnerability assessment of the built stock, which is generally based on the definition of appropriate fragility curves by means of different methods. A first type of methods uses an empirical approach with calibration from observed damage. A second group of methods uses mechanical models suitable to describe the structural behavior; however, because an in-depth geometric and structural characterization of the buildings is very time-consuming at the territorial level, these models must remain "as simple as possible" to limit the number of input parameters.

The aim of this work is to estimate the fragility of the Italian masonry buildings stock grouped in macro-typologies ISTAT (National Institute of Statistics), i.e. defined by construction age and number of stories; this is essential for deriving damage scenarios at territorial scale based solely on ISTAT information. Vulnus Vb 4.0 (2009), a software developed at the University of Padova, was found to be very useful for this purpose as it provides fragility curves of masonry buildings assessing the in-plane (IP) failure, the principal out-of-plane (OOP) mechanisms and the main typological-structural characteristics; judgments on the quality of information are also used to provide an upper and lower fragility limit. More than 500 buildings were examined with this software, appropriately chosen to guarantee a good statistical representation of the built stock. The information for each building was retrieved directly from the related projects and, in the case of missing information, reference was made to design manuals and codes, and to specific literature. Finally, the fragility results were processed to provide a mean fragility curve (representing the trigger of an IP - OOP mechanism) and a range of possible dispersion for each ISTAT macro-typology. These results can also be used to calibrate macro-seismic models of vulnerability in the literature, if the will is to represent this mechanical fragility in a more distributed way, i.e. with more damage states.

Keywords: Seismic Vulnerability of Residential Buildings, Macro-Typologies of Masonry Buildings, Seismic Risk at Territorial Level, Fragility Curves.

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1 INTRODUCTION

The seismic risk mitigation at national scale requires the vulnerability assessment of the built heritage, which is generally based on the definition of appropriate fragility curves. There are many methods for evaluating seismic vulnerability in the literature [1], which can be grouped into three main categories: empirical, analytical-mechanical and hybrid methods, with the latter using information from both mechanical and empirical methods. The former use empirical/observational approaches, i.e. they calibrate lognormal equations based on the observed damage [2, 3, 4]. For this purpose, databases collecting information from post-earthquake inspections, such as damage level and safety degree of the buildings affected, are very useful; in Italy, these databases are made available for the scientific community by the Civil Protection Department (DPC) through the IT platform called Da.D.O. (Observed Damage Database [5]). Analitical methods derive the fragility curves through numerical analyses, using (more or less simplified) mechanical models suitable to represent the seismic behaviour of specific structural typologies [6, 7, 8, 9, 10]. These methods, whose reliability requires appropriate and careful calibrations, have the potential to provide results with a wider range of validity than empirical methods; the latter, although theoretically should provide the best vulnerability estimates, are indeed calibrated on specific geographical areas hit by earthquakes.

One of the main difficulties in deriving the fragility of the building stock with mechanical methods is the need to gather a large amount of geometrical and structuralal information in order to appropriately define all the model parameters for each individual building, which requires very time-consuming surveys and cognitive studies. However, this difficulty could be overcome with the following approaches, which could also be applied together.

- Definition of seismic behaviour models that are robust but at the same time dependent on the smallest possible number of parameters, with careful sampling of buildings in order to obtain results that are as representative as possible at the territorial level (approach used);
- Development of innovative methods for both the rapid collection of key information (with modern digital and informatic techniques) and the statistical extrapolation (with Bayesian methods) of all other necessary data for the vulnerability estimates at territorial scale [11].

Therefore, this work aims to derive a mechianical fragility model for the Italian residential masonry constructions, grouped into building macro-typologies based on the ISTAT-2001 data (National Institute of Statistics, *www.istat.it* [12]), i.e. classified by construction age and number of storeys. For this purpose, it was used the software Vulnus Vb 4.0-2009 [13, 14, 15], developed at the University of Padova, which allows to obtain fragility curves of masonry buildings by assessing the probability of the in-plane shear failure and that of the main out-of-plane mechanisms (with linear kinematic analyses), as well as the main typological and structural characteristics; in addition, expert judgements on the quality of the information can be taken into account to provide, through the theory of fuzzy sets, an upper and lower boundary of fragility. By using this software, the individual fragilities of more than 500 buildings were calculated. These buildings were chosen based on the criteria of representativeness of the various classes of buildings in relation to the national context. Then, the fragility results were processed, still respecting the representativeness criteria, in order to obtain a mean fragility curve and a range of possible dispersion for each ISTAT macro-typology; the mechanical fragility curves thus obtained refer to the triggering of a specific mechanism, in-plan or out-of-plane, and therefore can be associated with an intermediate damage state (between moderate and severe).

Finally, with the aim of providing a more "distributed" fragility model, i.e. a model which defines the damage exceedance probability for multiple damage states, a possible calibration procedure, based on other fragility models of literature, is presented and applied to the mean fragility curves of each building class: such a fragility model, mechanical-heuristic, can therefore be more conveniently used for seismic risk analyses at territorial scale.

2 ANALYTICAL METHOD (VULNUS) FOR THE FRAGILITY ASSESSMENT

Vulnus 4.0 (Figure 1a) is a software developed at the University of Padova, originally by A. Bernardini, R. Gori and C. Modena and later updated by M.R. Valluzzi with the help of G. Benincà, E. Barbetta and M. Munari [14, 15].

Vulnus firstly calculates the in-plan and out-of-plane resistance parameters of buildings with a load-bearing masonry structure; in addition, it provides forecasts of expected seismic damage by returning fragility curves from the processing of geometrical and typological data. In particular, the necessary information are: the complete geometry of the building (in plan and elevation), the main mechanical characteristics of the material (specific weight, compressive and tensile strength), the type of floors and roofs (lightweight, heavy, balanced, un-balanced, …), the presence/absence and efficiency of toothings and the state of maintenance of the building.

The Vulnus methodology is based on the evaluation of the critical horizontal accelerations (*a*) which, when applied to the building masses, causes the activation of the main out-of-plane collapse mechanisms for each single walls and of the in-plane shear failure of parallel wall systems (or almost parallel), with the latter assumed as rigidly coupled by the floors. These critical accelerations are then returned in terms of minimum trigger coefficients *a/g* (with *g* the acceleration of gravity), which are defined as indices *I1* and *I2* for the in-plane and out-of-plane mechanisms, respectively.

In particular, index *I1* is defined as the ratio between the sum of the shear strengths of parallel wall systems (or almost parallel) and the total weight of the building; the shear strength is calculated in the average plane of the wall and for the weakest direction between the principal ones; this index is then eventually corrected, in the case of irregularities in plan and elevation, to take into account the possible non-uniform distributions of normal and tangential tensions.

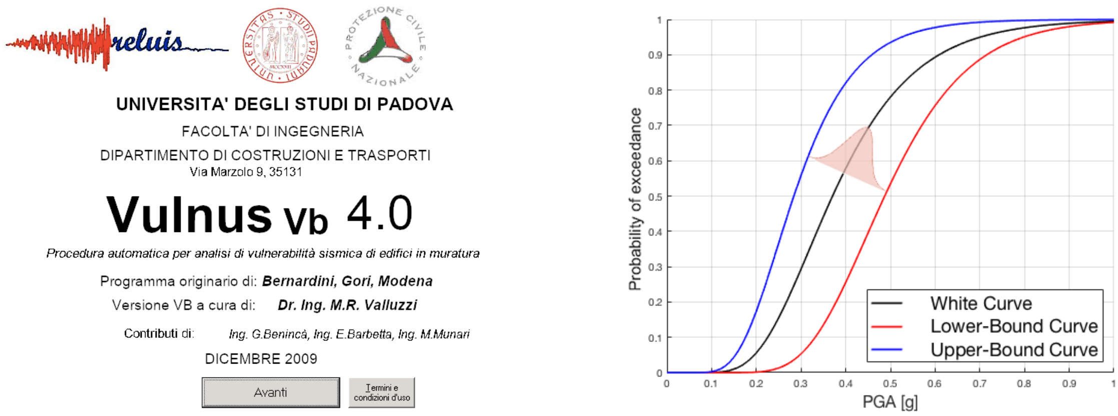
I2 index, instead, corresponds to the minimum value of the sum of two indexes, *I2′* and *I2″*, which represent the minimum trigger coefficients (*a*/*g*) of the kinematic mechanisms related to vertical and horizontal masonry strips, respectively, evaluated for each wall. Specifically, *I2′* evaluates the resistance of vertical strips of masonry (1 metre wide) for the following possible mechanisms: global overturning of the wall, overturning of the last storey, flexural failure of the last storey. *I2″*, instead, evaluates the arch resistance of horizontal strips of masonry (1 metre high) for the following mechanisms: flexural failure and arch compression failure of the last storey, global overturning and flexural failure of the shoulder of the compression arch at the last storey, and detachment mechanism of the transverse wall at the last storey.

In addition to *I1* and *I2*, a third index *I3* is also evaluated. It consists of a weighted sum of the scores that must be given to the various parameters of the “Second Level” form of G.N.D.T. [16] (besides the geometrical ones already evaluated in the definition of *I1* and *I2*); this index is provided in a normalized form between 0 and 1 (where *I3*=0 represents a building constructed according to anti-seismic regulations). This index considers qualitative factors (not included in the other two indices) and therefore represents the propensity of the building to be damaged by an earthquake. In particular, *I3* allows us to take into account also the conservation state of the building as well as the possible structural interventions that turned out to be worse for the seismic response.

Once the indices *I1*, *I2* and *I3* have been calculated, the vulnerability analysis can be carried out. Vulnus uses fuzzy set theory, transforming the indices into fuzzy subsets according to their interval of definition; this theory is based on the impossibility of defining an element in an univocal way and introduces the possibility of dealing with concepts that do not have exact boundaries. In particular, the fuzzy theory allows us to take into account the uncertainties associated with the parameters not directly measured and the variability of the mechanical parameters of materials, as well as any errors in the survey phase.

Through the "fuzzy sets", Vulnus calculates three cumulative probability distributions (fragility curves), which represent the probability of equaling or overcoming the acceleration of triggering an in-palne or out-of-plane mechanism. Two of these curves, representing the most extreme conditions, are defined as "Lower-Bound" and "Upper-Bound"; the other curve, defined as "White", is the most likely one and therefore represents an average vulnerability of the building (see Figure 1b).

The damage state (*DS*) to be associated with these fragility curves, based on expert judgment, is between moderate and severe; with reference to the EMS 98 damage scale, defined on five *DS* (between *DS*1, i.e. slight damage, and *DS*5, i.e. collapse), these curves represent an intermediate *DS* between 2 and 3, conveniently defined here as “*DS*2-3”. The reason is that these curves refer to the attainment of the average in-plane shear resistance or to the triggering of an out-of-plane mechanism, which are necessary but not sufficient conditions to activate the process of collapse of the structure (which requires a further contribution of seismic energy); in particular, if the triggering of an out of plane mechanism calculated with linear kinematic analysis can reasonably be associated with a DS2, the achievement of the medium shear strength of the building certainly represents a higher damage level, DS3.



(a) *(b)*

Figure 1 – (a) Vulnus 4.0; (b) example of White, Upper- and Lower-Bound fragility curves from Vulnus.

3 DEFINITION OF THE SAMPLE OF REAL BUILDINGS ANALYSED

As already discussed, the use of analytical methods to derive building stock fragilities at territorial scale requires very expensive and time-consuming cognitive studies in order to collect the many necessary information (geometrical, typological and structural). For this reason, the number of buildings that can be analysed with this approach is generally an order of magnitude lower than that generally analysed by using empirical approaches; therefore, the sampling phase of the buildings is very important and should be done appropriately in order to obtain results that are as representative as possible on a territorial scale.

To this end, a simple but effective grouping of the built heritage into macro-classes should be defined, on the basis of the principal factors that influence the building vulnerability; this is necessary both to address the sampling and to simplify the assessments of seismic fragility on a territorial scale, which consists in defining the average fragility curves for the classes of buildings identified.

The vulnerability of masonry structures is clearly influenced by many factors, such as: geometrical parameters (plan distribution and dimension of the lateral resistant systems, number of storeys, regularity in elevation, possible presence of adjacent buildings), material resistances, constructive and typological characteristics (in particular, for floors and roof) and construction details. Although these factors are extremely variable for buildings, a significant correlation can be found between them and the building construction periods; this is reasonable considering the historical evolution of the technological knowledge, the construction techniques, the material performance and the building codes. Therefore, a first grouping into building macro-typologies can be made by construction age.

A second grouping parameter that should significantly influence the building vulnerability is the number of storeys, as it is related to the total inertia seismic forces.

Another factor that greatly influences the vulnerability estimates at territorial scale is the geographical location: indeed, residential constructions belonging to different regions, or even to specific areas or municipalities of the same region, could show significant differences due to specific building traditions and local building materials. In the absence of sufficient information, the geographical position was not used as grouping parameter for the definition of the building classes, but this factor was taken into account through a widespread sampling that involved several Italian regions and municipalities.

Table 1 reports the building macro-typologies defined in this study, with indications relating to: number of buildings analysed, regions and number of regions and municipalities involved in the sampling, for each macro-typology. The parameters that define the macro-typologies are simple information that can be easily obtained, at national level, from ISTAT data [12]; this classification, which is quite simplified, was found to be effective (as will be shown in a future publication) for large-scale seismic risk assessments (i.e., on a municipal or greater scale).

As Table 1 shows, at least 80 buildings for each macro-typology were analysed. This quantity was considered sufficient for each class, due to the negligible variation in the average fragility with increasing number of case studies. However, for the construction period Pre-19, associated with the greatest seismic vulnerability and variability, the number of buildings considered is much greater and exceeds 200 cases, thanks to the availability of a lot of information and previous research studies carried out at the University of Padova.

Macro-typologies of masonry buildings										
Construction age	Pre-1919		1919-1945		1946-1960		1961-1980		Post 1980	
No. storeys	≤ 2	≥ 3	≤ 2	≥ 3	≤ 2	≥ 3	≤ 2	≥ 3	≤ 2	≥ 3
Database of buildings analysed										
No. buildings	205		80		80		80		80	
No. regions	3		5		4		2		4	
No. municipalities	8		8		6		3		10	
Regions *(buildings; municipalities)*	Abruzzo (*31;1*) Umbria (*43;2*) Veneto (*131;5*)		Emilia (*20;2*) Lazio (*13;1*) Lombardia (*23;2*) Trentino (*9;1*) Veneto (*15;2*)		Friuli (*33;1*) Lazio (*22;1*) Toscana (*10;1*) Veneto (*15;3*)		Friuli (*64;1*) Veneto (*16;2*)		Emilia (*35;4*) Lazio (*7;1*) Toscana (*13;2*) Veneto (*25;3*)	

Table 1 – No. of buildings, regions and municipalities involved in this study for all building macro-typologies.

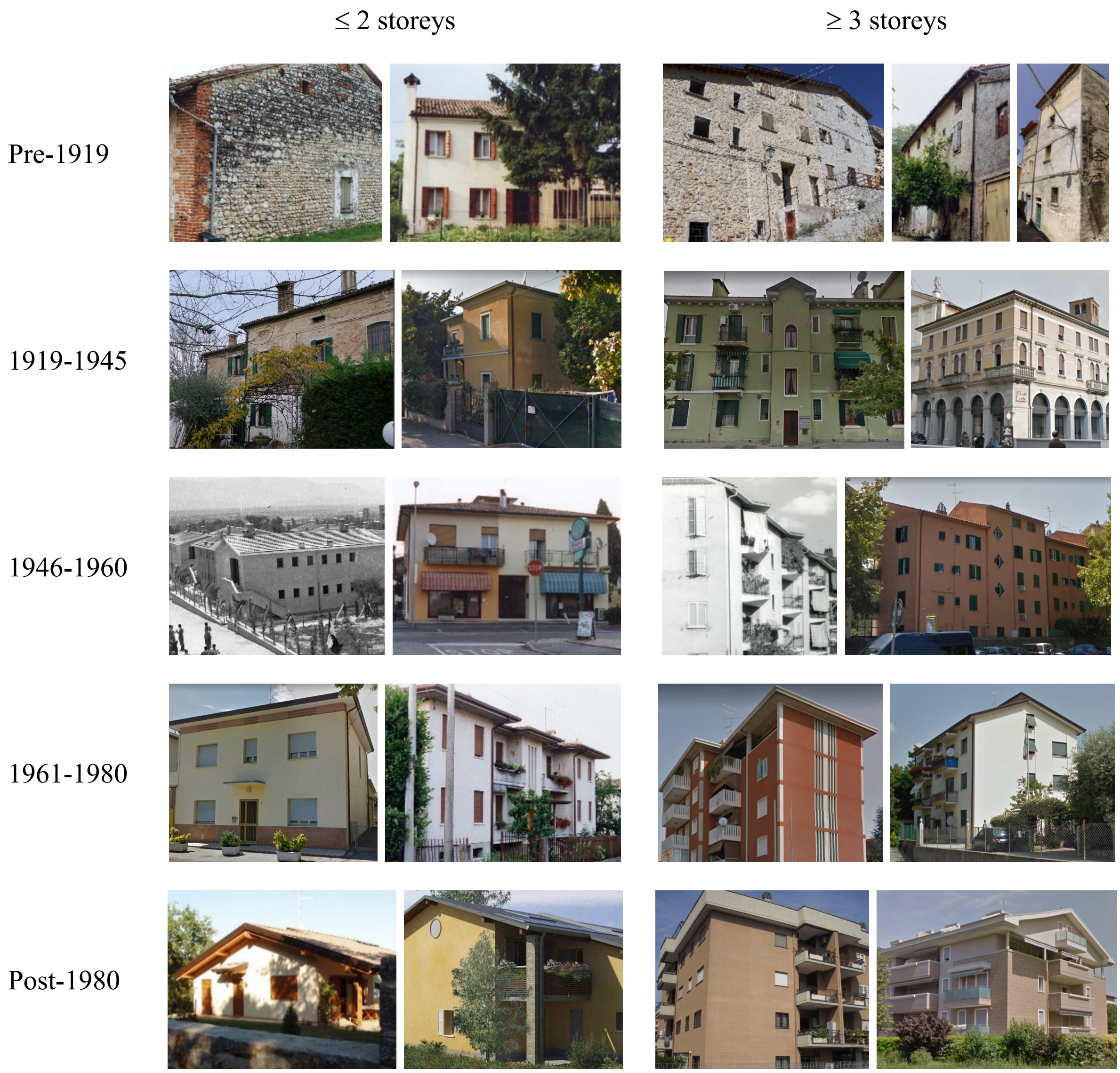


Figure 2 - Photos of some buildings analysed for the various macro-typologies.

In order to take into account the representativeness of the building stock for each macro-typology in terms of number of storeys, the building distribution of Figure 3 was derived from ISTAT-2001, and shows the masonry residential buildings by number of storeys and construction age.

Another important information to make a properly representative sampling is the distribution of buildings by typology or dimension (single houses, terraced houses, small or medium-sized apartment buildings, etc.); in the absence of such information at national level, we referred to another equivalent distribution, still obtained from the ISTAT-2001 database, which shows the residential buildings by number of dwellings (inside each building) and number of storeys. In particular, this information is available only in aggregate terms, i.e. without distinction between construction ages and construction materials (masonry, concrete or other), and therefore was used only as a qualitative reference to address the building sampling.

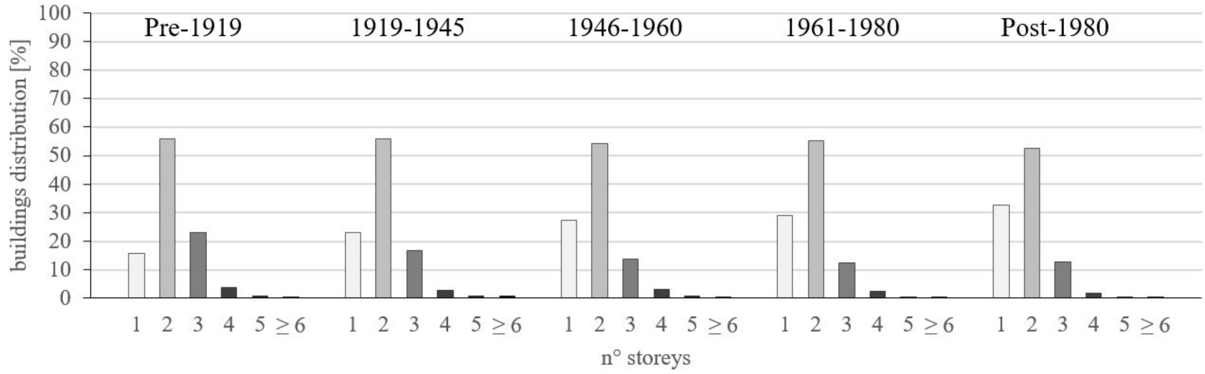


Figure 3 - Distribution of masonry residential buildings by No. of storeys and construction age (ISTAT 2001).

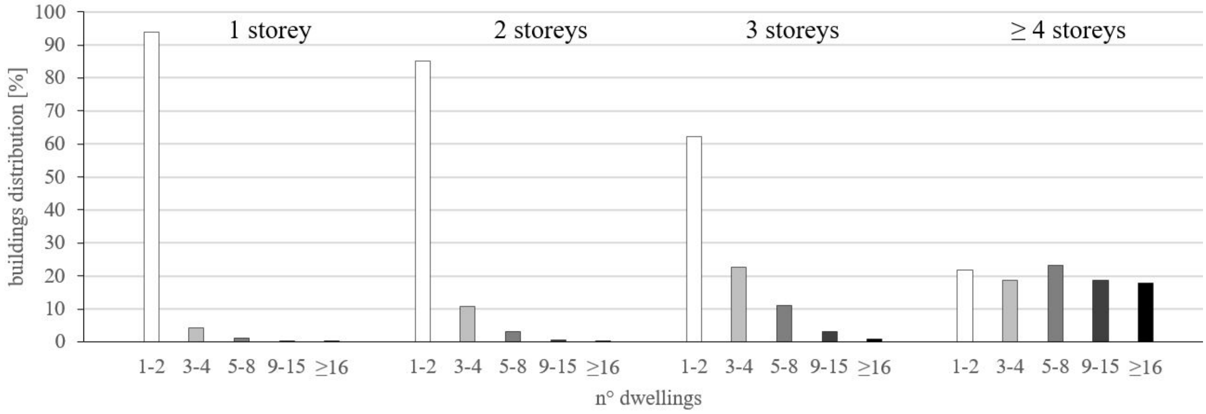


Figure 4 - Distribution of residential buildings by No. of dwellings and No. of storeys (ISTAT 2001)

As already mentioned, a mechanical fragility model require collecting a series of information for each building or case study examined, such as geometry, technology and structural characteristics. For this purpose, several sources of information were used, often associated with specific construction periods.

With regard to the period Pre-1919, many surveys conducted in previous years by the research group of the University of Padova (particularly carried out for master's or PhD [15] theses) were collected, analysed and used (when appropriate) for this study.

As concerns the period 1919-1945, most information (as plans, sections, materials – when specified, typology of floors and roofs) was derived from different projects contained in some project collection books as: "*Ville. 68 Esempi di ville e case di campagna"* and *"Case d'abitazione in Italia"* by B. Moretti (1946 and 1947) [17, 18] and from the manual "*Composizione della casa"* by I. Ceccarini (1952) [19].

For the period 1946-1960, the principal information regarded public housing projects and was derived from the "INA-Casa State" intervention plan, a plan which aimed to increase the employment of workers in the post-war period.

Other data, for both the period 1946-1960 and the following one 1961-1980, were found in the digitised archive of the Municipality of Pordenone (kindly provided by the municipal technical office), containing projects of single houses and apartment buildings with (often) indications about the materials and the construction technologies adopted.

For the last period, Post-1980, it was not possible to identify specific sources with relevant and numerous information, so most of the projects for residential buildings were obtained from the main Real Estate Agencies websites.

Finally, several projects were also kindly provided to us by engineering offices and some typological projects were taken from the manual *"Composizione della casa"* by I. Ceccarini [19]; the latter is available in different editions and contains standard layouts, which were useful to widen the building sample examined for each construction age.

All this information collected was substantially complete regarding the building geometry (i.e., plans, sections, elevations), but it was often missing about material characteristics, typology of floors and connection effectiveness (presence or absence of ring-beams). In order to gather as much information as possible among these missing, the following sources were used: TABULA project [20], which provides data at national level, with regards to the predominant material used for the vertical structures, about the typological-dimensional characteristics of buildings for different construction ages and building types (detached house, terraced house, multi-family building and block of apartments); technical architecture manuals [21, 22, 23, 24, 25, 26, 27, 28], which were used to deepend, for each construction period, the research on typological characteristics and construction materials. For the period Post-1980, some useful information was also found in the legislation in force at that time. Finally, other information about characteristics and resistances of materials was gathered from the Table C8A.2.1 of Circolare No. 617 (2 febbraio 2009).

The representativeness of the developed building database is shown in Figure 5 and Figure 6 through a comparison with the previous building distributions shown in Figures 3 and Figure 4 and obtained from the ISTAT-2001 database. In particular, in Figure 5, the unit (i.e., 100%) is related to buildings grouped into two building height classes, according to the building macro-typologyes, i.e. up to two storeys and with more than two storeys.

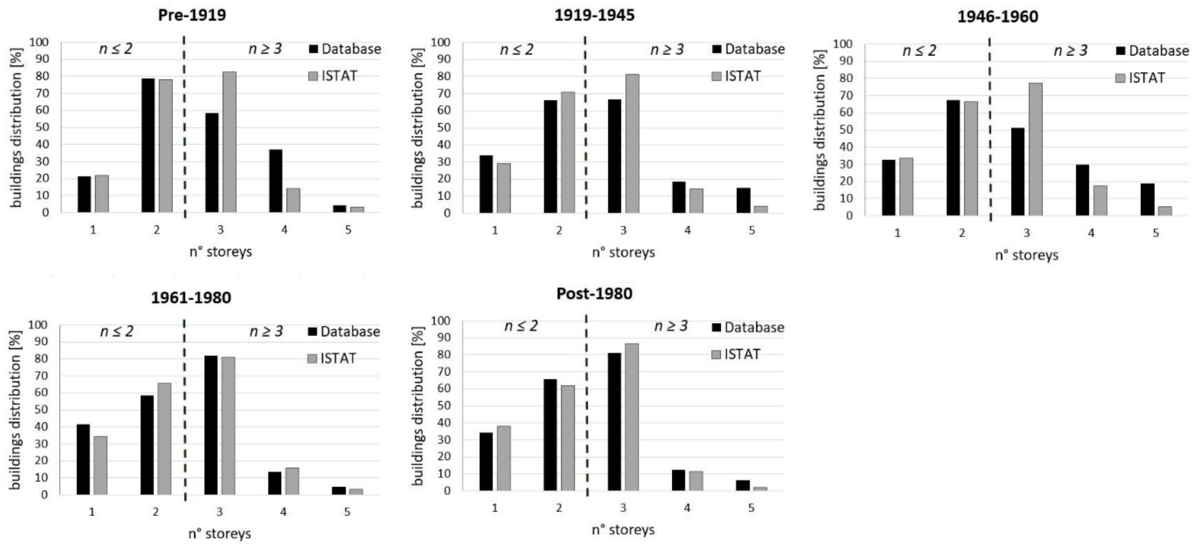
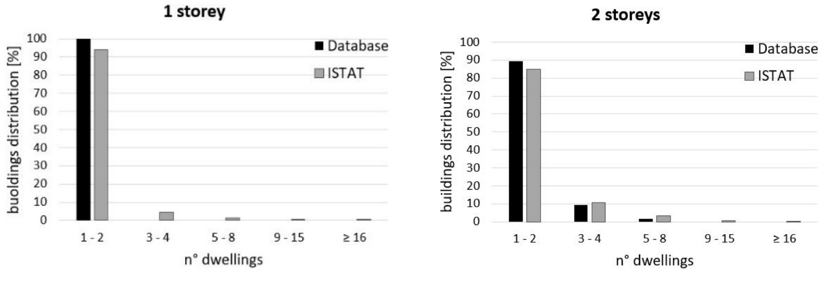


Figure 5 – Comparison of the building distribution by No. of storeys, between ISTAT 2001 and the database created, for each construction age.



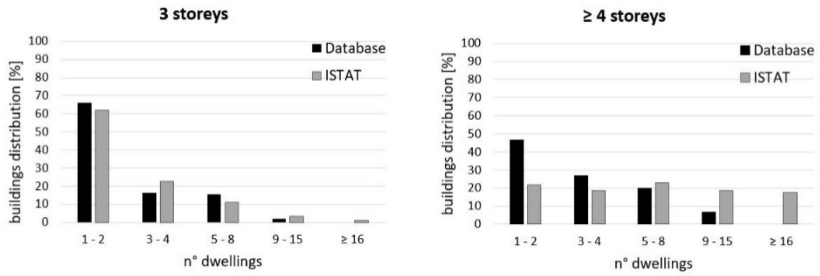


Figure 6 - Comparison of the building distribution by No. of dwellings, between ISTAT 2001 and the database created, for each class of No. of storeys.

4 DERIVATION OF THE MECHANICAL FRAGILITY CURVES

For all 525 sampled buildings, Vulnus 4.0 was used to calculate the three fragility curves, defined as "White", "Upper-Bound" and "Lower-Bound", which refer to a damage state between moderate (DS2) and severe (DS3), for this reason called DS2-3 (as explained in Section 2). In particular, since these curves are provided by points, a first elaboration was necessary in order to transform them into cumulative lognormal probability functions; in particular, the related values of mean (μ) and standard deviation (β) were obtained by adopting the criterion of maximum likelihood. The comparison between Vulnus and lognormal curves was generally good, as shown in Figure 7 as an example.

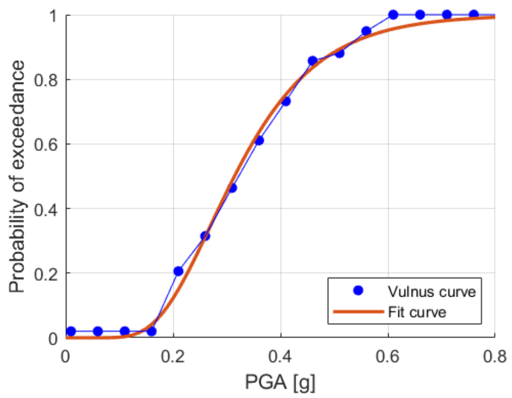


Figure 7 - Example of logonormal fit of a Vulnus curve

The methodology adopted to define the mechanical fragility model for the building macro-typologies defined in Table 1 is briefly described below; this was applied separately for the White, Upper- and Lower-Bounds curves.

1. For each municipality analysed, calculation of the mean fragility curve among those related to the buildings with the same construction period and number of storeys (from 1 to 5, with steps of 1).
2. Calculation of the average fragility curve between the mean fragility curves of the municipalities, always related to the buildings with the same construction period and number of storeys (from 1 to 5, with steps of 1).
3. Calculation of the fragility curve representative of the macrotypology as weighted average of the fragility curves obtained at point 2, separately for buildings with number of storeys (n) ≤ 2 and ≥ 3; the weights are the percentages of the statistical distribution of masonry buildings by number of storeys obtained from ISTAT 2001 (see Table 2).

In general, buildings belonging to the same macro-typology but located in different municipalities could present a quite different vulnerability due to specific building traditions and local building materials; therefore, in the absence of sufficient information about the representativeness of the sampled buildings at national or regional level, the same importance was assumed for all municipalities, i.e., only one fragility curve for each municipality – the average one – was used to define the fragility model (Steps 1 and 2). However, this procedure makes losing the representativeness of the buildings with respect to the national context (on which the building sampling was based); therefore, this representativeness was restored with the Step 3, by means of appropriate weighted averages.

Contruction age	Pre-1919		1919-1945		1946-1960		1961-1980		Post 1980	
No. storeys (*n*)	1	2	1	2	1	2	1	2	1	2
% of buildings with n ≤ 2	*0.22*	*0.78*	*0.29*	*0.71*	*0.33*	*0.67*	*0.34*	*0.66*	*0.38*	*0.62*

Contruction age	Pre-1919			1919-1945			1946-1960			1961-1980			Post 1980		
No. storeys (*n*)	3	4	5	3	4	5	3	4	5	3	4	5	3	4	5
% of buildings with n ≥ 3	*0.83*	*0.14*	*0.03*	*0.82*	*0.14*	*0.04*	*0.78*	*0.17*	*0.05*	*0.81*	*0.16*	*0.03*	*0.86*	*0.12*	*0.02*

Table 2 – Percentage of masonry buildings, by construction age and number of storeys, with respect to the total buildings with a number of storeys ≤ 2 (top) and ≥ 3 (bottom), according to ISTAT 2001.

As an example, Figure 8 shows the main calculation phases to obtain the "White" fragility model for the construction age Pre-1919; the same procedure was followed to evaluate the Upper and Lower-Bounds fragilities, as well as the fragility of the other construction periods.

Finally, Figure 9 shows the overall results of the mechanical fragility model obtained, i.e. the mechanical fragility curves White, Upper- and Lower-Bound (associated with a damage state DS2-3) for all the building macro-typologies examined.

These results show that the construction age and the number of storeys are both significant factors for the vulnerability assessment at territorial scale (as expected). The fragility of the various building macro-typologies is fairly distributed and it increases as the number of storeys and the age of building increases. The greatest variation occurs between the construction periods 19-45 (similar to the Pre-19) and 46-60: this is clearly due to the improvement in the material performance and in the construction techniques that occurred in those years.

In addition, Figure 9b shows that the possible dispersion interval, i.e. the range between the Upper- and Lower-Bound curves, becomes more important for the periods after 1946, and this is particularly true for the less vulnerable classes (i.e., 61-80 with 1-2 storeys and Post-80) because the Lower-Bound curves are associated with always lower values of exceedance probability (reasonable considering the high seismic performance of buildings well constructed in recent years). Such dispersion intervals in the definition of fragility should be appropriately taken into account for the seismic risk estimates at territorial scale.

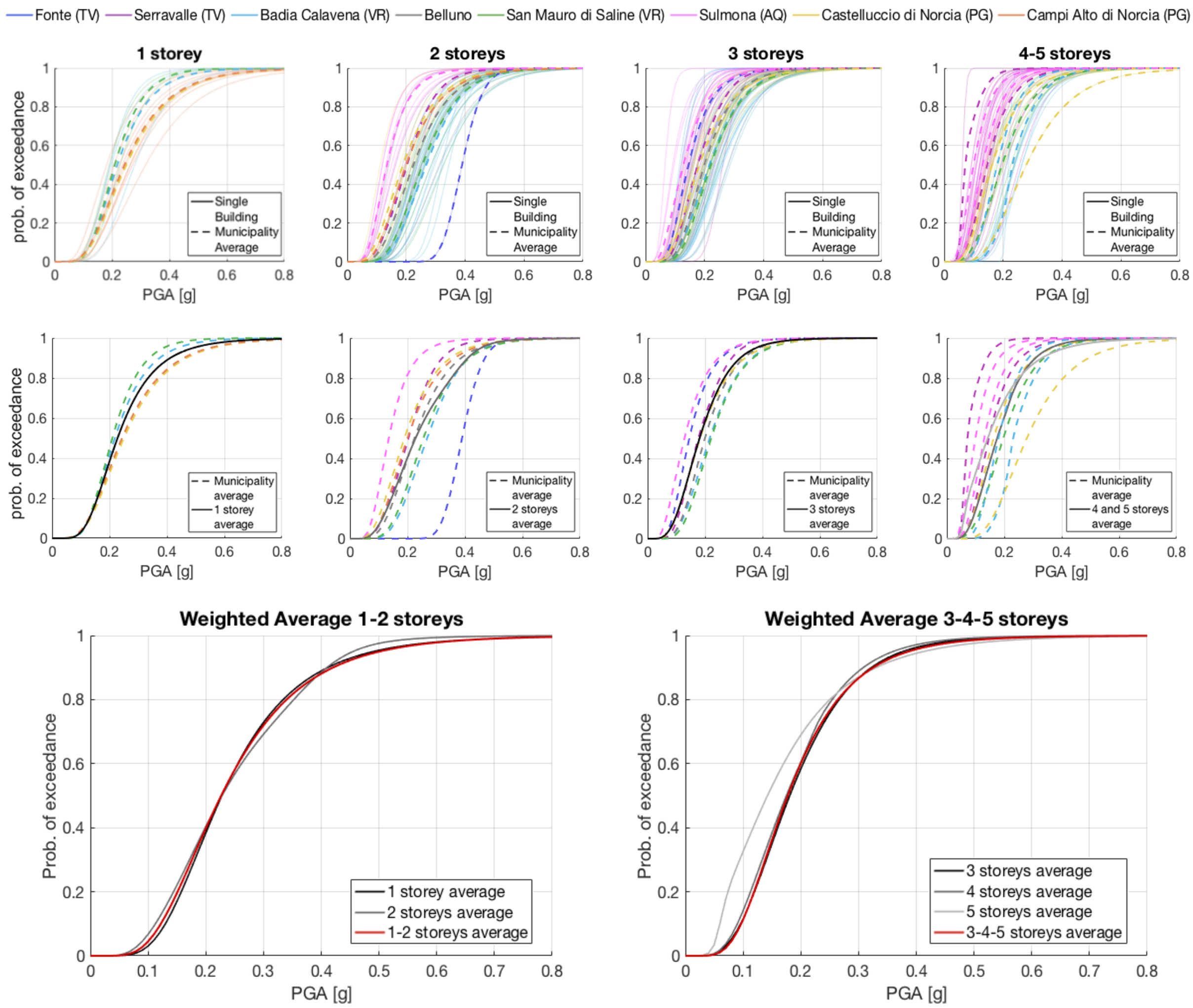
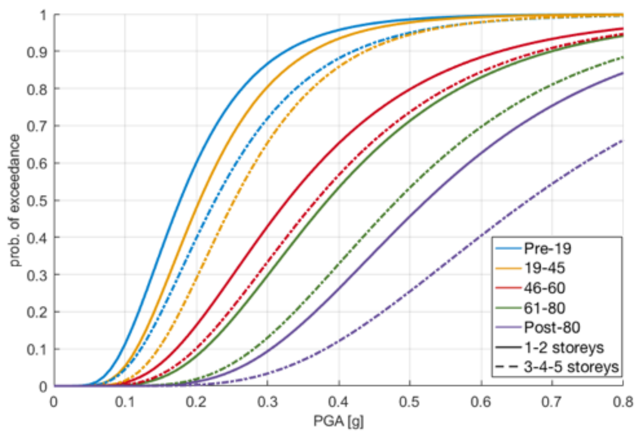
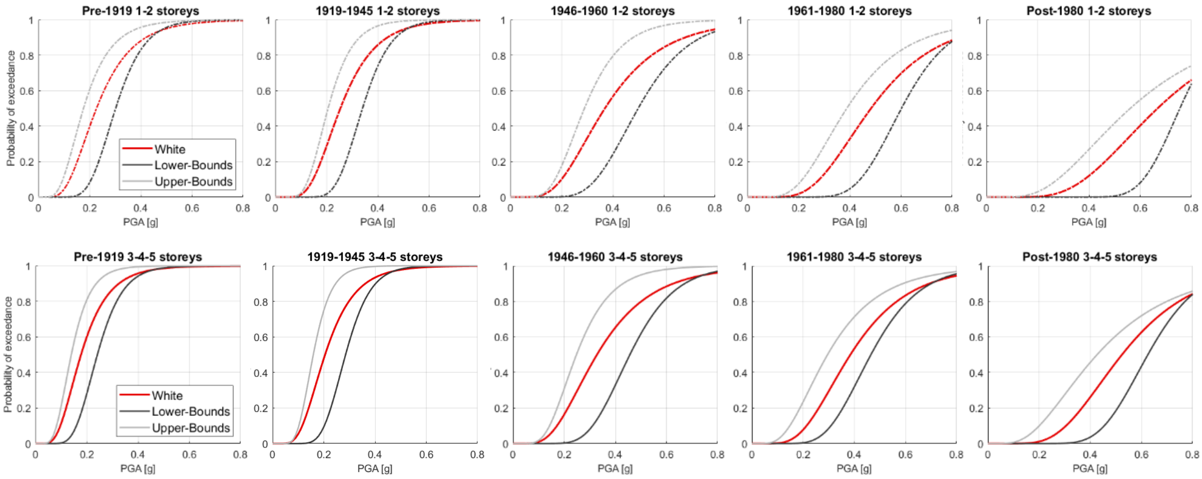


Figure 8 – Procedure for defining fragility curves by macrotypology: example shown for the age Pre-1919.



(a)



(b)

Figure 9 - Mechanical fragility curves associated with a moderate-several (DS2-3) damage state, for all macro-typologies analysed: *(a)* White curves; *(b)* Upper-Bound, White and Lower-Bound curves.

5 HEURISTIC FRAGILITY MODEL CALIBRATED ON MECHANICAL CURVES

As explained above, the mechanical fragility curves obtained for each ISTAT macro-typology refer to an intermediate damage state between moderate-DS2 and severe-DS3, according to the EMS98 scale (from DS1 to DS5), i.e. DS2-3.

In order to represent the seismic fragility in a more distributed way, i.e. on five damage states (DS), the fragility model of Lagomarsino and Cattari [29] was taken as a reference, which derives from the macroseismic vulnerability model of Giovinazzi and Lagomarsino [30]; however, differently than Lagomarsino and Cattari [29], the correlation law between macroseismic intensity and PGA was chosen according to Margottini et al. [31]. The resulting values of mean (μ) and standard deviation (β) for each fragility curve of this reference macroseismic model are reported in Table 3, and they refer to five DS and six vulnerability class (from A to F, according to the EMS98 scale).

This macroseismic model can than be calibrated on the mechanical fragility model previously obtained, thus deriving an "heuristic" fragility model on a mechanical basis. To this end, the main procedural steps adopted in this study are described below.

1 - For each vulnerability class of the macroseismic model, an average fragility curve (DS2-3) was calculated between those associated with DS2 and DS3, resulting therefore comparable with the mechanical fragility curves from Vulnus.

2 - For each mechanical fragility curve, the optimal linear combination between the curves DS2-3 of the macroseismic model was evaluated by means of a genetic algorithm (NSGA-II, i.e. Non-dominated Sorting Genetic Algorithm [32]); the aim was the minimization of two objectives sometimes conflicting, i.e.: the absolute error between the curves, calculated according to the criterion of the least squares, and the relative error between the curves, calculated as difference between the positive and negative areas between the curves. This optimization, and thus the results of the calibration, depends on the extension of the range of PGA assumed, chosen in this study between 0 and 0.8g, with the latter value representing a reasonable upper-bound for the expected peak ground accelerations in Italy.

3 - Once the optimal coefficients of linear combination associated with the various vulnerability classes are calculated, these can finally be used to generate a set of fragility curves (associated to the five DS) which is related to the mechanical fragility curve examined.

This procedure should be applied for all the mechanical fragility curves obtained in the previous fragility model, i.e., White, Lower- and Upper-Bounds curves, for each building macro-typology.

Figure 10 shows the calibration of the DS2-3 curves of the macroseismic fragility model with respect to the White fragility curves of the mechanical model, for all the building macro-typlogies. Figure 11 shows instead, as an example, the set of fragility curves of the heuristic fragility model so obtained, with regards to the White mechanical fragility and for two construction ages (Pre-1919, Post-1980).

Vulnerability class	DS1		DS2		DS3		DS4		DS5	
	μ [g]	β [-]	*μ [g]*	β [-]	*μ [g]*	β [-]	*μ [g]*	β [-]	*μ [g]*	β [-]
A	*0,0420*	0,5110	*0,0746*	0,5331	*0,1204*	0,5278	*0,1943*	0,5332	*0,3449*	0,5120
B	*0,0693*	0,5111	*0,1230*	0,5331	*0,1986*	0,5279	*0,3209*	0,5358	*0,5822*	0,5710
C	*0,1144*	0,5111	*0,2030*	0,5331	*0,3278*	0,5285	*0,5305*	0,5411	*0,9707*	0,5859
D	*0,1887*	0,5110	*0,3349*	0,5331	*0,5408*	0,5288	*0,8732*	0,5384	*1,5693*	0,5715
E	*0,3112*	0,5092	*0,5517*	0,5293	*0,8883*	0,5230	*1,4173*	0,5257	*2,452*	0,5448
F	*0,5088*	0,4881	*0,8934*	0,5060	*1,4175*	0,4984	*2,1972*	0,4951	*2,3782*	0,5358

Table 3 - Means *(μ)* and standard deviations *(β)* of the reference macroseismic model [29, 31].

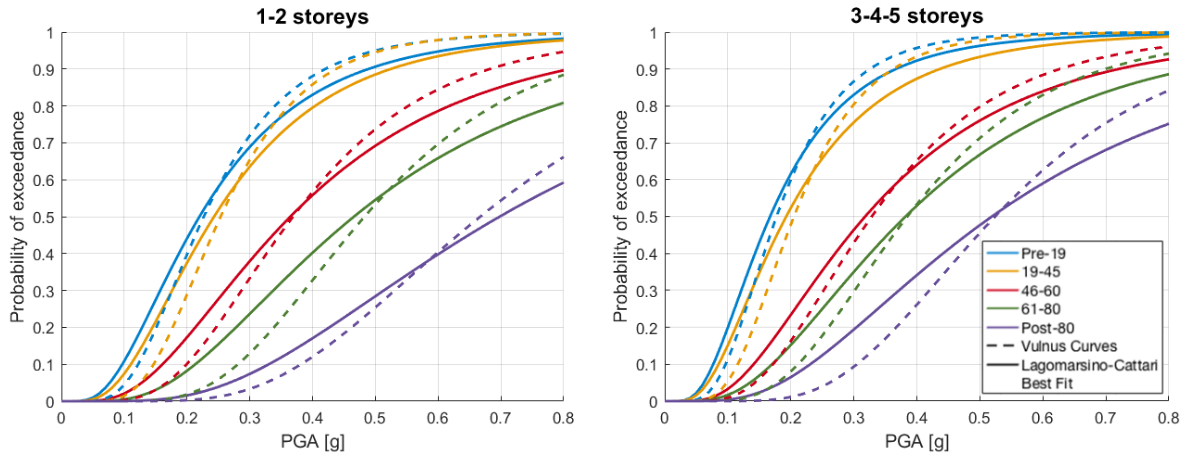


Figure 10 - Optimal fit between mechanical curves (White) and DS2-3 curves of the reference model (Table 3).

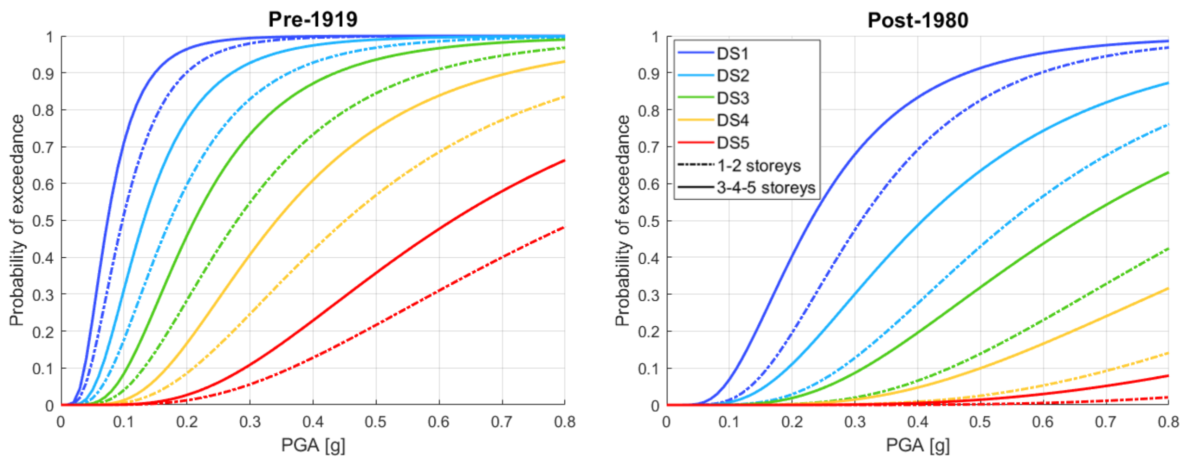


Figure 11 – Example of fragility sets from the heuristic model calibrated on mechanical basis.

6 CONCLUSIONS

- The paper presented a study aimed at obtaining a mechanical fragility model for the evaluation, at territorial scale, of the seismic vulnerability of residential masonry buildings belonging to the Italian built heritage. In particular, the fragility was derived for building macro-typologies defined on the basis of key information from ISTAT-2001, such as construction age and storey number.
- Vulnus Vb 4.0 (2009), a software developed at the University of Padova, was used for this study, as very suitable for this purpose: it provides fragility curves of masonry buildings assessing the in-plane failure, the principal out-of-plane mechanisms (with linear kinematic analyses) and the main typological-structural characteristics. Moreover, expert judgements on the quality of the information are used to provide an upper and lower fragility boundary, by means of the fuzzy sets theory.
- More than 500 masonry buildings were evaluated in order to derive the mechanical fragility model. These buildings were chosen based on the criteria of representativeness of the various building classes in relation to the national context. The fragility curves of each building were processed, still respecting the representativeness criteria, in order to obtain a mean fragility curve and a dispersion range for each ISTAT class. This fragility refers to the triggering of a specific mechanism, in-plan or out-of-plane, and therefore is associated with a “moderate-severe” damage state.
- Finally, with the aim to extend this mechanical fragility model to a more “distribute” fragility model, i.e. with exceeding probabilities defined for multiple damage levels, a possible heuristic approach is presented and applied; the new heuristic model is more suitable for seismic risk estimates at territorial level.
- The mechanical fragility model obtained shows that the construction age and the number of storeys are both significant factors for the vulnerability assessment at territorial scale (as expected). Also, the fragility of the various building macro-typologies is fairly distributed; the greatest variation is found between the construction ages 19-45 (similar to the Pre-19) and 46-60. Moreover, the possible dispersion interval in the definition of fragility becomes more important for less vulnerable macro-typologies (construction periods after 1946). In general, such a dispersion should be taken into account in the seismic risk estimates at territorial scale.
- Possible future developments: (*i*) increase in the sample of buildings analysed; (*ii*) refinement in the classification of buildings, considering other factors such as: the geographical region/area of the building (often associated with specific building traditions and local building materials), the building size and the number of residential units, and also the presence or absence of seismic retrofit interventions.

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