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A MACROSEISMIC METHOD FOR THE VULNERABILITY ASSESSMENT OF BUILDINGS

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SUMMARY

A seismic risk analysis addressed to earthquake emergency management and protection strategies planning, requires territorial scale evaluation; to this aim a macroseismic method for the vulnerability assessment of built-up area is presented. The method is derived, in a conceptually rigorous way, by the use of Probability and of Fuzzy Set Theory, considering Macroseismic Scale definitions. Damage Probability Matrices are evaluated for the six vulnerability classes considered by the EMS98 scale; vulnerability curves are drawn for these classes and for different building typologies. An analytical equation, interpolating the curves, is introduced as a function of an only one parameter the Vulnerability Index; it correlates the seismic input, in term of Macroseismic Intensity, with the physical damage, summarized by the mean value of the beta distribution. An average Vulnerability Index is associated to each building typology, which may be refined on the basis of a seismic behavior modifier factor, and of a regional factor. A different uncertainty is associated with the vulnerability assessment and the consequent damage evaluation depending on the quantity and quality of data available for the analysis. By the use of statistical correlations, consequences scenarios (collapse, unfit for use buildings, deaths and injuries, homeless) and physical losses can be estimated.

INTRODUCTION

The vulnerability analyses on an ordinary built-up area on a territorial scale require evaluations of a large number of samples; the use of structural calculation models cannot be proposed both due to the difficulty of identifying simple but reliable models, and for the quantity of data that would be necessary to collect in the field. The methodologies available must therefore base themselves on few empirical parameters and make use as much as possible of poor or existent data, in order to limit the high costs and the long time generally required for field survey operations.
In the United States, and nowadays also in Europe, the most recent trends in the field of vulnerability methods for scenario risk analysis, lead to operating with simplified mechanical models; they are essentially Capacity Spectrum based procedures (Freeman [1], HAZUS [2]) which permit to evaluate the expected seismic performance by the comparison, in spectral coordinates (Sd, Sa), between the seismic demand, represented by Acceleration-Displacement Response Spectra (ADRS), adequately reduced in

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order to take into account the inelastic behavior (Fajfar [3]), and the seismic capacity. For territorial vulnerability assessment scopes, Capacity Spectrum procedures do not necessarily refer to capacity curves obtained by pushover analyses, but they ascribes to each building typology, bilinear capacity curves in term of yielding (Dy, Ay) and ultimate (Du, Au) capacity points; these curves vary depending on several geometrical and technological parameters of the building (number of floors, code level, material strength, drift capacity).

Such approach provides reliable results if applied to a built-up area characterized by a typological building homogeneity and by consolidated seismic design codes. This is not the case of European Union regions where seismic codes are very different and where various typologies of masonry buildings can be distinguished in the territory. In Europe, the common employment of capacity based methods needs, yet, a robust experimental validation, at least on the traditional masonry constructions; for this reason, statistical methods based on damage observations are ordinary applied.

The vulnerability assessment is, in this case, performed in terms of qualitative parameters: the buildings are classified in vulnerability classes, and a DPM Damage Probability Matrix (DPM) is ascribed to each one (Whitman [4], Corsanego [5], Coburn [6]) or scores are attributed to the buildings considering their typological, structural, geometric, constructive characteristics; a simple model is then defined in function of the evaluated score connecting the seismic input to the damage (FEMA 310 [7], FEMA 154 [8], Benedetti [9]). The first ones, referred as typological methods, are usually employed if poor data are statistically available on a territory, while the seconds, known as inspection or rating methods, require a field survey, sometime performed in a quick or simplified way.

As the available data are often limited and do not concern all the building typologies and all the Intensities that it would be necessary to represent in a model, the probabilistic processing of the observed data, at the root of observational methods, is supported or completely replaced by other approaches such as expert judgement (ATC13 [10]), neural network system (Dong [11]) or Fuzzy Set Theory (Sanchez-Silva [12]).

In this work a method is proposed that, considering the multitude of experiences carried out during these years in the field of vulnerability approaches, overcomes the distinction between typological and rating methods and allows carrying out a vulnerability analysis with a single approach (intermediate between typological and semeiotic approaches), graded to different levels according to the quantity and quality of the available data (that are not tied down to a specific form) and the size of the territory. The method is derived in a theoretically rigorous way, starting from EMS 98 Macroseismic Scale (Grunthal [13]) definitions; for this reason the method is considered applicable and reliable for all the European Regions on the contrary to others proposals that, being strongly connected with the data employed for their derivation, can be generalized with difficulty. The proposed method has been subsequently verified on the basis of data observed after different earthquakes in different countries.

EMS 98 VULNERABILITY CURVES

The vulnerability model implicitly contained in EMS-98 Macroseismic Scale

The basic concept of a macroseismic method is that if the aim of a Macroseismic Scale is the measure of an earthquake severity, from the observation of the damage suffered by the buildings, it can, in the same way, represent, for forecast purposes, a Vulnerability Model able to supply, for a given intensity, the probable damage distribution.

If the old scales of intensity made very generic reference to the distribution of damage for the different intensities of the earthquake, with no distinction with regard to the construction typology (almost all the built-up area was masonry), modern scales contain an ever-more precise description of the distribution of damage for the different building typologies. In particular, the MSK-76 scale [14] and the recent EMS-98 contain a clear definition of typologies and of the distribution of damage correlated to each degree of intensity.

The methodology proposed here makes reference to the EMS-98 scale, not just because it is the most recent and probably the one that will be used in the future at the European level, but especially for the quality and the detail with which the building typologies, the degrees of damage and the quantities are defined. Like the other Macroseismic Scales, EMS-98 makes references to Vulnerability Classes, which are a way to group together buildings characterized by a similar seismic behavior; seven classes (from A to F) of decreasing vulnerability are introduced and, for each of them, the Intensity that can be estimated from a certain damage pattern, is supplied in terms of damage matrices. A damage matrix contains the probability for the buildings belonging to a certain vulnerability class, to suffer a certain damage level for a given intensity (Table 1). EMS 98 damage description is discrete and considers 5 damage grades plus the absence of damage.

Table 1. Damage model provided by EMS-98 for Class B and Class C.

Class B					
Damage L. Intensity	1	2	3	4	5
V	Few				
VI	Many	Few			
VII		Many	Few		
VIII			Many	Few	
IX				Many	Few
X					Many
XI					Most
XII					

Class C					
Damage L. Intensity	1	2	3	4	5
V					
VI	Few				
VII		Few			
VIII		Many	Few		
IX			Many	Few	
X				Many	Few
XI					Many
XII					Most

These damage matrices can be interpreted for vulnerability scopes, but the model that they provide is vague and incomplete. The definition of the damage amount is, indeed, provided in a vague way through the quantitative terms “Few”, “Many”, “Most” as the aim is a post-earthquake survey and a precise determination of quantities is not envisaged. Moreover, the distribution of damage is incomplete as the Macroseismic Scale only considers the most common and easily observable situations (for example, no information is provided for Damage Grade 3, 4 and 5 in the case of I = VI and Vulnerability Class B, see Table 1).

The incompleteness matter

In order to solve the incompleteness matter, the damage distributions of earthquakes occurred in the past has been considered; the idea is to complete the EMS-98 model introducing a proper discrete probability distribution of damage grade. The binomial distribution could be a possibility as it has been successfully used for the statistical analysis of data collected after 1980 Irpinia earthquake (Italy) (Braga [15]); but the simplicity of this distribution, which depends on only one parameter, does not allow defining the scatter of the damage grades around the mean value.

Sandi [16] observes that the dispersion of the binomial distribution is too high, when you consider a detailed building classification; this may lead to overestimate the number of buildings suffering serious damages, in the case of rather low values of the mean damage grade. The distribution that better suits the specific requirements is the beta distribution (also employed in ATC-13 [10]):

$$PDF:\ p_\beta(x)=\frac{\Gamma(t)}{\Gamma(r)\Gamma(t-r)}\,\frac{(x-a)^{r-1}\,(b-x)^{t-r-1}}{(b-a)^{t-1}}\qquad a\le x<b \tag{1}$$

$$\mu_x = a+\frac{r}{t}\,(b-a) \tag{2}$$

where a, b, t and r are the parameters of the distribution; μ_x is the mean value of the continuous variable x, which ranges between a and b.

In order to use the beta distribution, it is necessary to make reference to the damage grade D, which is a discrete variable (5 damage grades plus the absence of damage); for this purpose, it is advisable to assign value 0 to the parameter a and value 6 to the parameter b. Starting from this assumption, it is possible to calculate the probability associated with damage grade k (k=0,1,2,3,4,5) as follows:

$$p_k = P_\beta(k+1) - P_\beta(k) \quad (3)$$

Following this definition, the mean damage grade, mean value of the discrete distribution (4), and the mean value of the beta distribution (2) can be correlated through a third degree polynomial (5).

$$\mu_D = \sum_{k=0}^{5} p_k \cdot k \quad (4)$$

$$\mu_x = 0{,}042 \cdot \mu_D^3 - 0{,}315 \cdot \mu_D^2 + 1{,}725 \cdot \mu_D \quad (5)$$

Thus, by (2) and (5), it is possible to correlate the two parameters of the beta distribution with the mean damage grade:

$$r = t(\,0.007\mu_D^3 - 0.0525\mu_D^2 + 0.2875\mu_D\,) \quad (6)$$

The parameter t affects the scatter of the distribution; if t=8 is used, the beta distribution looks very similar to the binomial distribution.

The vagueness matter

Solved the matter of incompleteness by the discrete beta distribution, in order to derive numerical DPM for EMS 98 vulnerability classes, it is necessary to tackle the problem of the vagueness of the qualitative definitions (few, many, most). As it is arbitrary translating the linguistic terms into a precise probability value, they can be better modeled as bounded probability ranges. The fuzzy sets theory (often proposed for seismic risk assessment methods) has offered an interesting solution to the problem, leading to the estimation of upper and lower bounds of the expected damage (Bernardini [17]). According to the fuzzy set theory the qualitative definitions can be interpreted through Membership Functions χ, (Dubois [18]). A membership function defines the belonging of single values of a certain parameter to a specific set; the value of χ is 1 when the degree of belonging is plausible (that is to say almost sure), while a membership between 0 and 1 indicates that the value of the parameter is rare but possible; if χ is 0, the parameter does not belong to the set.

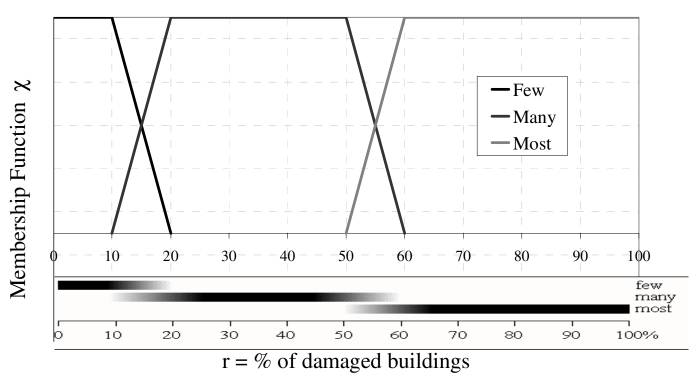

Figure 1. Percentage ranges and membership functions $\chi$of the quantitative terms Few Many Most.

Figure 1 shows the range of percentage corresponding to the quantitative terms (few, many, most) according to EMS-98: it emerges that while there are some definite ranges (few, less then 10%; many, 20% to 50%; most, more then 60%), there are situations of different terms overlapping (between 10% and 20% can be defined both few and many; 50% and 60%, both many or most). These qualitative definitions are interpreted through the Membership Functions χ in Figure 1

EMS-98 Damage Probability Matrices

Using the fuzzy sets theory and starting from EMS-98 definitions (Table 1), it is possible to build the DPM, through the discrete beta distribution (3). Reminding that to each value of parameter μ_D, having definitely assumed a=0, b=6 and for a fixed value of t, a damage grade distribution corresponds, it has been looked for μ_D values able to represent the terms "Few", "Many", "Most" in a plausible and then in a possible way according to the membership functions associated to the quantitative definitions. In order to make the operation easier a value t=8 may be used; anyway it has been verified how, for different values, the differences observed are negligible. From the probabilistic distributions corresponding to the computed μ_D values, the percentages of damage have been attributed to the different damage grades.

As an example it is possible to consider the vulnerability *class B* and the macroseismic intensity VI: according to Table 1, *many* buildings should suffer a damage of grade 1 (slight) and a *few* a moderate damage (grade 2). The plausible values of the parameter μ_D are the ones for which all EMS-98 quantity definitions must be respected in a plausible way; that is to say that the percentage of damage 1 is between 20% and 50% (*Many*), while the percentage of damage 2 is less then 10% (*Few*). The range of plausible values of μ_D is defined by two plausibility bounds, obtained when p_2=10% (upper bound) and when p_1=20% (lower bound). The possible values of the parameter μ_D are the ones for which all EMS-98 quantity definitions are plausible or possible, with at least one which is only possible. The ranges of possible values are adjacent to the plausible range, being defined by two possibility bounds, obtained when p_2=20% (upper bound) and when p_1=10% (lower bound). Table 2 shows for the vulnerability class B, the upper and lower bounds of the mean damage grade, related to plausibility and possibility; the corresponding distributions of the damage grades are shown: the dark and light grey cells correspond to the control definitions, the value that determines the bound is in bold character.

Table 2. Damage distributions and mean damage values related to the upper and lower bounds of plausibility and possibility ranges for class B.

Class B						
Damege Level Intensity VI	1 Many	2 Few	3	4	5	μ_D
B^+ Upper Plausible	32.0	**10**	1.9	0.2	0.0	0.68
B^- Lower Plausible	**20**	4.3	0.6	0.0	0.0	0.43
B^{++} Upper Possible	40.6	**20**	5.5	0.7	0.0	1.81
B^{--} Lower Possible	**10**	1.6	0.2	0.0	0.0	0.25

Repeating this procedure for each vulnerability class and for the different intensity degrees it is possible to obtain, point by point, the plausible and possible bounds of the mean damage. Connecting these points, draft curves are drawn, which define the plausibility and possibility areas for each vulnerability class, as a function of the macroseismic intensity (Fig. 2).

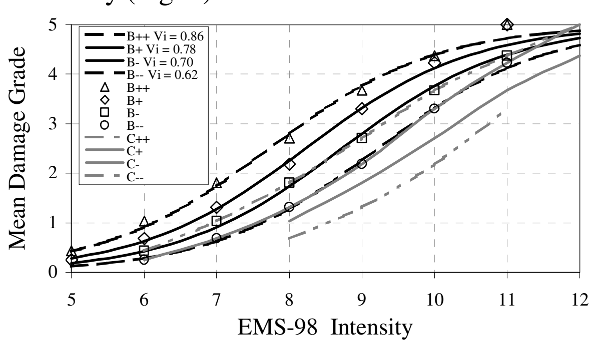

Figure 2. Class B and C plausibility and possibility curves and their interpolation.

Vulnerability Index and Vulnerability Curves

Observing the diagram of Figure 2, it stands out that there is a plausible area for each vulnerability class and intermediate possible areas for contiguous classes. In other words, the area between B+ and B- is distinctive of class B, while there is a contiguous area in which the best buildings of class B and the worse of class C coexist (the B- curve coincides with the C++ one; the B-- curve coincides with the C+ one). Another important outcome of the analysis above presented, is that curves in Figure 2 are, more or less, parallel; this is because the damage produced to buildings of a certain vulnerability class, because of an earthquake of a certain intensity, is the same caused by the following intensity degree to buildings of the subsequent vulnerability class. On the basis of these considerations a conventional Vulnerability Index V_I, defined inside the Fuzzy Set Theory, is introduced representing the belonging of a building to a vulnerability class. Vulnerability Index numerical values are arbitrary as they are only scores to quantify in a conventional way the building behavior (they represent a measure of the weakness of a building to the earthquake); for the sake of simplicity a 0-1 range has been chosen, allowing to cover all the area of possible behavior, being values close to 1 those of the most vulnerable buildings and values close to 0 the ones representative of the high-code designed structures.

Thus, the membership of a building to a specific vulnerability class can be defined by this vulnerability index (Fig. 3); in compliance with the fuzzy set theory they have a plausible range (χ=1) and linear possible ranges, representative of the transition between two adjacent classes.

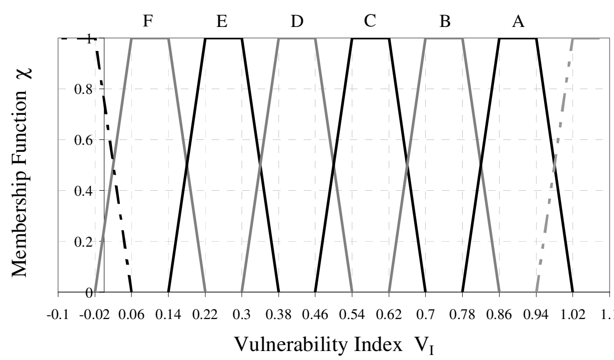

Figure 3. Vulnerability Index membership functions for EMS 98 vulnerability classes.

The fuzzy definition of the Vulnerability index (Fig. 3) is perfectly coherent with the considerations previously done relatively to the vulnerability curves; the membership functions of the six vulnerability classes have the same shape and are translated of the same quantity, according to the parallelism and the constant spacing between the curves (Fig. 2). According to the fuzzy definition of the Vulnerability Index, Table 3 shows the most probable value for each vulnerability class V_I^{c*}, the bounds V_I^{c-} V_I^{c+} of the uncertainty range, and the upper and the lower bound of the possible values $V_{I\ max}^{\ c}$ $V_{I\ min}^{\ c}$. It must be noticed (Fig. 3) that the partition of the fuzzy field is not restricted to –0.02 as the minimum value and to 1.02 as the maximum value; actually it is not possible to keep out the chance of buildings weaker than the one belonging to *class A* or building better designed than the one classified as *class F*.

Table 3. Vulnerability Index values for the vulnerability classes

	$V_{I\ min}^{\ c}$	$V_I^{\ c-}$	$V_I^{\ c*}$	$V_I^{\ c+}$	$V_{I\ max}^{\ c}$
A	1.02	0.94	0.9	0.86	0.78
B	0.86	0.78	0.74	0.7	0.62
C	0.7	0.62	0.58	0.54	0.46

	$V_{I\ min}^{\ c}$	$V_I^{\ c-}$	$V_I^{\ c*}$	$V_I^{\ c+}$	$V_{I\ max}^{\ c}$
D	0.54	0.46	0.42	0.38	0.3
E	0.38	0.3	0.26	0.22	0.14
F	0.22	0.14	0.1	0.06	-1.02

For the operational implementation of the methodology it is particularly useful to define and analytic expression, capable of interpolating the curves in Figure 2; the mean damage grade μ_D is given as a function of the macroseismic intensity I, only depending from the parameter the Vulnerability Index V_I:

$$\mu_D = 2.5\left[1 + tanh\left(\frac{I + 6.25 \cdot V_I - 13.1}{2.3}\right)\right] \tag{7}$$

THE VULNERABILITY INDEX EVALUATION

EMS 98 DPM and Vulnerability Curves have been evaluated for the 6 vulnerability classes considered by the scale. It is possible to refer the model directly to the building typologies making reference to EMS98 Vulnerability Table (Table 4), which contains a typological classification representative of the various building types in the European countries. It distinguishes, in the first place, constructions in function of the structural material: masonry, reinforced concrete, steel, timber; thus identifies different construction typologies for each category.

In spite of the detailed distinction of each type of building, it is recognized that the seismic behavior of buildings, in terms of apparent damage, may be subdivided by, at least, six vulnerability classes (Table 4). Thus, different types may behave in a similar way (see, for example, massive stone and unreinforced masonry with r.c. floors); on the other hand, it emerges that even if each type of structure is characterized by a prevailing vulnerability class, it is possible to find buildings with a better or worse seismic behavior, depending on their constructive or structural characteristics and every other parameter able to affect their earthquake resistance.

Table 4. Attribution of vulnerability classes to different building typologies.

Typologies		Building type	Vulnerability Classes					
			A	B	C	D	E	F
	M1	Rubble stone	■					
	M2	Adobe (earth bricks)	■	▒				
	M3	Simple stone	░	■				
	M4	Massive stone		▒	■	░		
	M5	Unreinforced M (old bricks)	░	■	░			
	M6	Unreinforced M with r.c. floors		▒	■	░		
	M7	Reinforced or confined masonry			░	■	▒	
Reinforced Concrete	RC1	Frame in r.c. (without E.R.D)	░	▒	■	░		
	RC2	Frame in r.c. (moderate E.R.D.)		░	▒	■	▒	
	RC3	Frame in r.c. (high E.R.D.)			░	▒	■	▒
	RC4	Shear walls (without E.R.D)		░	■	▒		
	RC5	Shear walls (moderate E.R.D.)			░	■		
	RC6	Shear walls (high E.R.D.)				░	■	▒
Stell	S	Steel structures			░	▒	■	▒
Tiber	W	Timber structures		░	▒	■	▒	

Situations: ■ Most probable class; ▒ Possible class; ░ Unlikely class (exceptional cases)

The idea highlighted by the EMS-98 scale, according to which the seismic behavior of a building does not only depends on the behavior of its structural system, but it involves other factors, has suggested the following definition of the Vulnerability Index:

$$\overline{V_I} = V_I^* + \Delta V_R + \Delta V_m \tag{8}$$

where V_I^* is a Typological Vulnerability Index, ΔV_R is the Regional Vulnerability Factor, ΔV_m represents a contribution to take into account the presence of seismic behavior modifiers.

Typological Vulnerability Index definition

Analogously to what done for quantity definition, EMS-98 table describes the different belonging of a typology to a vulnerability classes through linguistic terms (Table 4): “Most possible class”, “Possible Class”, “Unlikely class”. Even in this case, Fuzzy Set Theory can provide an useful contribution for the linguistic term interpretation. The different belonging of each typology to the vulnerability classes is

represented in a fuzzy way, by discriminating the most likely class (χ=1), the probable classes (χ =0.6) and the exceptional cases (χ =0.2) (Table 4).
It is possible to define the membership function of each building type, as a linear combination of the vulnerability class membership functions, each one considered with its own degree of belongings. As an example, the membership function of the massive stone masonry (M4) is shown (Fig. 4) and so defined:

$$\chi_{M4}(V_I) = \chi_C(V_I) + 0.6 \cdot \chi_B(V_I) + 0.2 \cdot \chi_D(V_I) \quad (9)$$

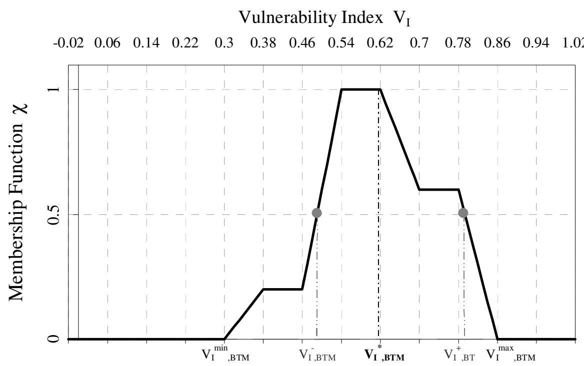

Figure 4. Vulnerability Index membership functions for M4 Massive Stone typology and V_I values.

From the membership function of each typology, five representative values of V_I have been defined (Fig. 4) through a defuzzification process (Ross [20]): the most probable value for the specific building type V_I^* (the typological vulnerability index) is computed as the centroid of the membership function; V_I^- and V_I^+, evaluated by a 0.5-cut of the membership function, represent the bounds of the uncertainty range of V_I^* for the specific building type. $V_{I\ min}$ and $V_{I\ max}$ corresponds to the upper and lower bounds of the possible values of $\overline{V}_I$ the final vulnerability index value, for the specific building type; whatever is the estimated amount for the behavior modifiers and the regional factor, the final vulnerability index has to comply with this possibility range.

$$Max\left(\overline{V}_I ; V_{I\,min}\right) \leq \overline{V}_I \leq Min\left(\overline{V}_I ; V_{I\,max}\right) \quad (10)$$

These values are represented in Figure 4 for Massive Stone masonry typology and reported in Table 5 for all the EMS-98 buildings typologies.

Table 5. Vulnerability Index values for the buildings typology.

Typologies		Building type	ulnerabilità Classes				
			$V_{I\,min}$	V_I^-	V_I^*	V_I^+	$V_{I\,max}$
Masonry	M1	Rubble stone	0.62	0.81	0.873	0.98	1.02
	M2	Adobe (earth bricks)	0.62	0.687	0.84	0.98	1.02
	M3	Simple stone	0.46	0.65	0.74	0.83	1.02
	M4	Massive stone	0.3	0.49	0.616	0.793	0.86
	M5	Unreinforced M (old bricks)	0.46	0.65	0.74	0.83	1.02
	M6	Unreinforced M with r.c. floors	0.3	0.49	0.616	0.79	0.86
	M7	Reinforced or confined masonry	0.14	0.33	0.451	0.633	0.7
Reinforced Concrete	RC1	Frame in r.c. (without E.R.D)	0.3	0.49	0.644	0.8	1.02
	RC2	Frame in r.c. (moderate E.R.D.)	0.14	0.33	0.484	0.64	0.86
	RC3	Frame in r.c. (high E.R.D.)	-0.02	0.17	0.324	0.48	0.7
	RC4	Shear walls (without E.R.D)	0.3	0.367	0.544	0.67	0.86
	RC5	Shear walls (moderate E.R.D.)	0.14	0.21	0.384	0.51	0.7
	RC6	Shear walls (high E.R.D.)	-0.02	0.047	0.224	0.35	0.54
Stell	S	Steel structures	-0.02	0.17	0.324	0.48	0.7
Tiber	W	Timber structures	0.14	0.207	0.447	0.64	0.86

The Behavior Modifier Factor

The Typological Vulnerability Index V_I^* computed for each typology can be increased or decreased on the basis of the vulnerability factors recognized inside a certain building. If a group of building, belonging to a certain typology, is considered, the Modifier Factor ΔV_m, is evaluated as follow:

$$\Delta V_m = \sum_k r_k \cdot V_{m,k} \qquad (11)$$

where r_k is the ratio of building affected by the behaviour modifier *k* characterized by a $V_{m,k}$ score.

Making reference to single buildings, the Behaviour Modifier Factor ΔV_m is simply the sum of the scores $V_{m,k}$ for the recognized behaviour modifiers.

The behavior modifiers identification has been made empirically, on the basis of the observation of typical damage pattern, taking into account also what suggested by several Inspection Forms (ATC 21 [21], Benedetti [9], UNDP/UNIDO [22]) and by previous proposal (Coburn [6]). The modifying scores V_m are attributed through expert judgment. They have been partially calibrated by the comparison with previous vulnerability evaluation; a further calibration is wished on the basis of damage and vulnerability data collected after earthquakes.

In Table 6 behaviour modifier factors and the corresponding scores are proposed for Masonry and Reinforced Concrete buildings.

Table 6. Scores for behavior modifier factors for Masonry and RC buildings

Behaviour modifier	Masonry		Reinforced Concrete ERD Level	Pre/Low	Medium	Hight
		V_{mk}		V_{mk}	V_{mk}	V_{mk}
State of preservation	Good	-0.04	Good	-	-	-
	Bad	+0.04	Bad	+0.04	+0.02	0
Number of floors	Low (1or 2)	-0.04	Low (1-3)	-0.02	-0.02	-0.02
	Medium (3,4 or 5)	0	Medium (4-7)	0	0	0
	High (6 or more)	+0.04	High (8 or more)	+0.08	+0.06	+0.04
Structural system	Wall thickness Wall distance Wall connections	-0.04÷+0.04				
Plan Irregularity	Geometry Mass distribution	+0.04	Geometry	+0.04	+0.02	0
			Mass distribution	+0.02	+0.01	0
Vertical Irregularity	Geometry Mass distribution	+0.04	Geometry Mass distribution	+0.04	+0.02	0
Superimposed flors		+0.04				
Roof	Weight, thrust and connections	+0.04				
Retroffiting Intervention		-0.08÷+0.08				
Aseismic Devices	Barbican, Foil arches, Buttresses	-0.04				
Aggregate Building: position	Middle	-0.04	Insufficient aseismic joints	+0.04	0	0
	Corner	+0.04				
	Header	+0.06				
Aggregate Building: elevation	Staggered floors	+0.04				
	Buildings with different height	-0.04÷+0.04				
Foundation	Different level foundations	+0.04	Beams	-0.04	0	0
			Connected beams	0	0	0
			Isoleted Footing	+0.04	0	0
			Short-column	+0.02	+0.01	0
			Bow windows	+0.04	+0.02	0

The Regional Vulnerability Factor

The range bounded by V_I-, V_I + is quite large in order to be representative of the huge variety of the constructive techniques used all around the different European countries.

A Regional Vulnerability Factor is introduced to take into account the typifying of some building typologies at a regional level: a major or minor vulnerability could be indeed recognized due to some traditional constructive techniques of a region.

According to this Regional Vulnerability Factor it is allowed to modify the V_I^* typological vulnerability index on the basis of an expert judgment or on the basis of the historical data available. The first case is achieved when precise technological, structural, constructive information exists attesting an effective better or worse average behavior with regard to the one proposed in Table 5. The second one occurs when data about observed damages exist; the average curve ($V_I = V_I^*$ in Equation 7) can be shifted in order to obtain a better approximation of the same data (Fig.5).

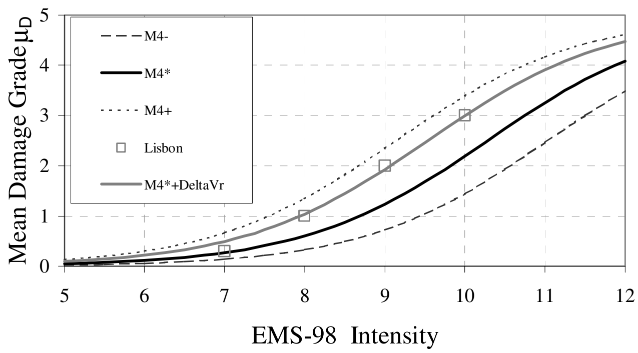

Figure 5. In Lisbon (Oliveira [23]) Massive Stone shows a better behavior than the average for M4 (Table 4): a ΔV_R=0.12 is applied.

Uncertainty Range in the vulnerability assessment.

The uncertainties affecting a seismic risk analysis are both epistemic and aleatory; in the proposed method only epistemic uncertainties are considered (aleatory uncertainties will be taken into account if a PSHA analysis is performed). In particular, vulnerability evaluations are affected by an uncertainty associated with the classification of the exposed building stock into a vulnerability class or into a building typology and by the uncertainty associated with the attribution of a characteristic behaviour to the vulnerability class or building typology (Spence [24]).

Both these two kinds of uncertainties are computed in the proposed approach, that provides the most probable vulnerability index and furthermore plausibility and a possibility range around it for each vulnerability class (Table 3) and for each building typology (Table 5).

It must be noticed how the uncertainty affecting building typologies is higher than the one computed for vulnerability classes; thus as the building typology behaviour has been deduced from the one observed from vulnerability classes and furthermore because with few data is more difficult to classify a building into a typology rather than into a vulnerability class.

But the knowledge of additional information, then the typological ones, limits the uncertainty about the building behavior; it is therefore advisable not only to modify the most probable value V_I^* (according to Equation 8), but also to reduce the range of its uncertainty ($V_I^- \div V_I^+$). This goal is achieved modifying the membership function through a filter function *f*, centered on the new most probable value $\overline{V_I}$, depending on the parameter ΔV_f, representing the width of the filter function, so defined:

$$f(V_I, V_I^*, \varDelta V_m, \varDelta V_R, \Delta V_f) = 1 \qquad if \quad \left|V_I - V_I^* - \Delta V_m - \varDelta V_R\right| \le \frac{\varDelta V_f}{2}$$

$$f(V_I, V_I^*, \varDelta V_m, \varDelta V_R, \Delta V_f) = 1.5 - \frac{\left|V_I - V_I^* - \Delta V_m - \Delta V_R\right|}{\varDelta V_f} \qquad if \quad \frac{\varDelta V_f}{2} \le \left|V_I - V_I^* - \Delta V_m - \varDelta V_R\right| \le \frac{3}{2}\varDelta V_f \tag{12}$$

$$f(V_I, V_I^*, \varDelta V_m, \varDelta V_R, \Delta V_f) = 0 \qquad if \quad \left|V_I - V_I^* - \varDelta V_m - \varDelta V_R - \Delta V_f\right| > \frac{3}{2}\varDelta V_f$$

The filter function is then multiplied by the membership function of an EMS 98 typology and the resulting function is afterwards normalized to a maximum value equal to 1, so obtaining the membership function of the specific set of buildings, which takes into account all the vulnerability factors:

$$\chi(V_I) = \frac{\chi(V_I) \cdot f(V_I, V_{I,}^*, \varDelta V_m, \varDelta V_f)}{max\left[\chi(V_I) \cdot f(V_I, V_{I,}^*, \varDelta V_m, \varDelta V_f)\right]} \tag{13}$$

The width ΔV_f of the filter function depends on the quantity and quality of available data. In Table 7 two values are proposed, in relation with the kind of data.

Table 7. Suggested values for ΔV_f in relation to data origin and quality

DATA ORIGIN	ΔV_f
Non specified existing data base	0.08
Data specifically surveyed for vulnerability purposes	0.04

For the sake of an easy operative application of the methodology the filter function can be substituted with an acceptable approximation, considering around the final vulnerability index value $\overline{V_I}$ an uncertainty range with a width equal to the value suggested in Table 7 depending on the data quality.

$$V_I^+ = +\frac{3}{2}\Delta V_f \qquad V_I^- = -\frac{3}{2}\Delta V_f \tag{14}$$

THE HAZARD REPRESENTATION

The Macroseismic Intensity is the most natural parameter to represent seismic input dealing with vulnerability methods derived from damage observation. Considering how it has been obtained, EMS-98 Macroseismic Intensity is the input parameter to be used for the proposed approach.

The objection that intensity is not a valid parameter to characterize seismic input, being a discrete quantity, may be overcome, bearing in mind that, even intermediate values, conceptually lacking in meaning in a macrosesimic survey, may be used for forecast purposes; in the proposed model, intensity is considered as a continuous parameter and as well, regarding hazard scenarios, intensity attenuation laws provide continuous values.

Even though the considerable developments of seismological research for the definition of physical-mechanical seismic input representation, intensity remains an important reference parameter in seismic risk studies as, only by means of intensity, it is possible to make use of the essential information contained in the catalogs of historical seismicity

It is true that the evaluation of an intensity hazard scenario cannot take advantage from the progresses made in the field of modeling of mechanisms of source, of the propagation of waves and of seismic micro-zoning, that, on the contrary, a physical-mechanical hazard definition (PGA, displacement and acceleration spectrum) can make use of; a big amount of uncertainty has to be computed as employing Intensity, a set of knowledge is overlooked on respect to a physical mechanical hazard representation. On the other hand getting, by proper correlations, an intensity hazard representation from different input parameters implies the introduction of a bigger amount of uncertainty because of the huge scatter characterizing these correlations.

A big uncertainty in the hazard definition is not, however, so worrying; seismic risk analyses have often the aim of comparative evaluations, in order to identify the most “at risk” areas in a territory or in a town.

Nevertheless these considerations on behalf of Macroseismic Intensity, this parameter is, for the physical characterization of the seismic input, definitely less meaningful than Displacement and Acceleration Spectra. Whit regard to the structures, it is comparable to an only PGA (Peak Ground Acceleration) representation, that, non-released from a spectrum does not provide any information about the dynamic behavior of a structure. In contrast with PGA, the soil amplification is an aspect non-well represented by the use of Macroseismic Intensities. With regard to Intensity hazard representation, soil amplifications are taken into account increasing, locally, the intensity evaluated (TC4-ISSMFE [25]).

Anyway, the undifferentiated increase on Intensity for a certain soil type is incorrect, as it does not allow taking into account the differences in the dynamic amplification connected with the fundamental frequencies of both the soil and the structure. In order to overcome this limitation, it is proposed, in the follow, to consider this possible dynamic amplification in term of Vulnerability Index Modifiers.

Soil Modifiers Definition

The Vulnerability Index Modifiers, defined in order to take into consideration “site effects” have been evaluated making reference to the Eurocode 8 [26] for the dynamic characterization of both the building categories and the soil types. Regarding the soil, reference is made to the definition of the Horizontal Elastic Response Spectrum provided by EC8 for different Ground Types.

Concerning the buildings, the fundamental period T_1 for Masonry and Reinforced Concrete categories is evaluated for three different ranges of height (low, medium, high) applying the expression proposed by EC8 and a 3 meters inter-story value (Table 8).

Table 8. Fundamental period T_1 for Masonry and RC buildings

	M-Low	M-Medium	M-High	RC-Low	RC-Medium	RC-High
Floors	2	4	6	3	7	12
T_1	0.19	0.32	0.44	0.39	0.74	1.10

For each of this period a multiplier factor f_{PGA} of the PGA is evaluated that generate a seismic action able to produce on a certain building category (T_I fixed) built on a certain soil, the same effect if it was built on Rock (Ground Type A). In figure 6 the Elastic Response Spectra are shown able to reproduce the same seismic action suffered by the three height classes Reinforced Concrete Building built on a Ground Type D. The PGA factors are evaluated as follow:

$$f_{PGA} = \frac{Sa[T_1]_{Soil_K}}{Sa[T_1]_{Soil_A}} \qquad (15)$$

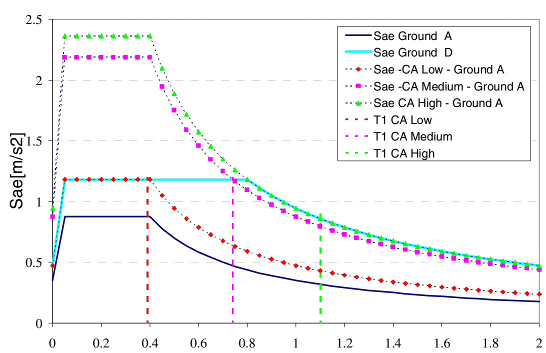

Figure 6. Ground Type A Elastic Response Spectra able to reproduce the same seismic action suffered by three high classes Reinforced Concrete Building built on Ground Type D.

The resulting factors for the different Ground Types (Table 9) are in accordance with the amplification factors of spectral ordinates proposed by other approaches [25].

Table 9 PGA multiplier factors f_{PGA} evaluated for EC8 Ground Types and for different building categories.

	B/A	C/A	D/A	E/A		B/A	C/A	D/A	E/A
M-Low	1.2	1.15	1.35	1.4	RC-Low	1.2	1.15	1.35	1.4
M-Medium	1.2	1.15	1.35	1.4	RC-Medium	1.5	1.725	2.5	1.75
M_Alti	1.32	1.265	1.485	1.54	RC-High	1.5	1.725	2.7	1.75

According to I - PGA correlations to a *PGA* factor f_{PGA} an Intensity Increment ΔI corresponds. For the (16) equation the correlation proposed by Guagenti & Petrini [27] has been employed.

$$\Delta I = \frac{\ln(f_{PGA})}{0.602} \qquad (16)$$

ΔI increments (Table 10) are coherent with the ones proposed in literature.

Table 10 Intensity Increments ΔI evaluated for EC8 Ground Types and for different building categories.

	B/A	C/A	D/A	E/A		B/A	C/A	D/A	E/A
M_Low	0.30	0.23	0.5	0.56	RC_Low	0.30	0.23	0.5	0.56
M_Medium	0.30	0.23	0.5	0.56	RC_Medium	0.67	0.91	1.52	0.93
M_High	0.46	0.39	0.66	0.72	RC _High	0.67	0.91	1.65	0.93

Assuming the proposed formula for macroseismic vulnerability curves (7) as the link between Intensity and Vulnerability, a Vulnerability Increment ΔV corresponds to the Intensity Increment ΔI.

$$\Delta V = \frac{\Delta I}{6.25} \qquad (17)$$

Vulnerability index soil modifiers, evaluated for different building typologies, height classes and ground types, are shown in Table 11. They are computed in the final Vulnerability Index evaluation according to equation (11).

Table 11 Vulnerability Increments ΔV evaluated for EC8 Ground Types and for different building categories.

	B/A	C/A	D/A	E/A		B/A	C/A	D/A	E/A
M_Low	0.04	0.03	0.08	0.09	RC _Low	0.04	0.03	0.08	0.09
M_Medium	0.04	0.03	0.08	0.09	RC_Medium	0.10	0.15	0.24	0.15
M_High	0.07	0.06	0.10	0.12	RC_High	0.10	0.15	0.26	0.15

PHISICAL DAMAGE AND CONSEQUENCES EVALUATION

Damage distributions

The computation of the final vulnerability index $\overline{V_I}$ allows estimating a mean damage grade μ_D for a forecasted intensity scenario (7); coherently with the definition of the proposed method, μ_D values are distributed according to a beta distribution (1).

V_I values are affected by a cognitive uncertainty described by a membership function χ (Fig. 3); these cognitive uncertainty is reflected on μ_D values according to equation (7); in order to avoid loosing in the damage assessment the uncertainty characterizing the vulnerability index evaluation, the reflected cognitive uncertainty on μ_D values, must be considered jointly with the scatter of the beta distribution.

It is demonstrated (Ayyub [19]) that, considering a probabilistically distributed random variable X with σ as its standard deviation, and assuming that the random variable X has a cognitive uncertainty in its mean value μ, described by a membership function χ, the variance of the fuzzy-random variable is

$$\overline{\sigma}^2 = \sigma_P{}^2 + \sigma_F{}^2 \tag{18}$$

where $\sigma_P{}^2$ is the variance of the probabilistic distribution (the beta distribution in this work) and $\sigma_F{}^2$ is the variance of the membership function χ.

From observed damage data on different vulnerability classes, it results that the overall variance $\overline{\sigma}^2$ is equal to the one of a binomial distribution (Braga [15]) (equivalent to a beta distribution with t=8). Making reference to the membership function χ (Figure 3) defined for the vulnerability index of vulnerability classes, the $\sigma_F{}^2$ evaluation is immediate; therefore the variance $\sigma_P{}^2$ for the damage distribution corresponding with each μ_D value is calculated according to formula (19).

Regarding this $\sigma_P{}^2$ and the different $\sigma_F{}^2$ evaluated depending on the quantity and the quality of data employed for the assessment (Tables 3, 5, 7) the total variance $\overline{\sigma}^2$ to be used for the damage distributions in all the different cases considered in this work is evaluated.

For the sake of an easier operative implementation of the proposed approach, the corresponding t values defining the beta function are provided (Table 12).

Table 12 Values of the t parameter for vulnerability classes, building typologies and filter function.

		t
Vulnerability Classes		8
Building Typologies	M1, M2, M3	6
	M4, M5, M6, M7, RC4, RC5, RC6	4
	RC1, RC2, RC3, S, W	3
Filter function	ΔV_f=0.08	8
	ΔV_f=0.04	12

Physical damage, consequences and losses damage scenarios

Substituting the evaluated μ_D in the (6), for the advised value of the parameter t (Table 12), the beta function is defined and the damage distribution is evaluated.

Knowing the damage distribution, it is possible to recognize the ratio of collapsed building (as the percentage of buildings suffering a 5 damage degree) and the ratio of damaged and unfit for use buildings, by the use of empirical correlations based on the consequences observation after past earthquakes. On the basis of the damage evaluation, and by the use of proper correlations (Coburn [6], Tiedemann [28], Hazus [2], Bramerini [29]) it is also possible to estimate the amount of homeless and injured people.

With regard to the economical losses connected to the structural damage, a correlation between the mean damage grade μ_D and the damage index D_I (ratio between the repair and the reconstruction cost) (Giovinazzi [30]) is introduced:

$$\mu_D = 5 \cdot D_I^{0.57} \tag{19}$$

The damage representation can be directly obtained in term of fragility curves; they express the probability that the expected damage of a structure will exceed a fixed damage grade during the ground shaking (in terms of macroseismic intensity).

$$P(D \geq D_k) = \sum_{j=k}^{5} p_j \tag{20}$$

where p_j = probability associated with damage grade j (j=0,1,2,3,4,5).

Once the μ_D is evaluated and for a fixed value of the parameter t, the beta distribution is completely determined and the fragility curves for the damage grade correspond to its cumulate function.

$$P(D \geq D_k) = 1 - P_\beta(k) \tag{21}$$

CONCLUSIONS

In this work a new macroseismic approach is proposed that preserves the compatibility with preceding methods, but overcomes the distinction between typological and ratings methods.

The method can be employed both with statistical existent data (as none specific structure is required for the building information) or properly surveyed data and it can be implemented both for the vulnerability assessment of single buildings and of built-up areas (as census tracts, or municipality areas) . This allow performing quick and less expensive assessment, so that risk analysis can be achieved also in countries where it is no possible to invest a lot of money for risk prevention and management.

According to its definition, the method is sufficiently representative of the different European building typologies; it is particularly useful for the vulnerability characterization of traditional masonry constructions as, for these building types, simplified mechanical approaches require a further validation.

Thanks to these positive features, the vulnerability evaluations are comparable even thought performed in different countries and with data of different origin and quality.

Moreover a clear analytical definition allows the easy implementation in a GIS environment; there, crossing the hazard and the vulnerability, the development of the damage scenario is an obvious following step; consequences on buildings (damaged, collapsed and unfit for use) and on people can be evaluated together with the economic losses. The use of the analysis results in risk mitigation becomes an effective tool: the possibility of a constant updating of the data and the rather fast computational operation allow decision makers to construct simply different scenarios testing the effectiveness of different set of mitigation strategies.

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