VULNERABILITY AND DAMAGE ASSESSMENT OF CURRENT BUILDINGS IN ITALY: AN APPLICATION TO SULMONA TOWN

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ABSTRACT :

A macroseismic method for the vulnerability assessment of current buildings and an application to the town of Sulmona (Italy) are presented in this paper. The method is derived making reference to the EMS-98 Macroseismic Scale, which implicitly contains a model of vulnerability. Fuzzy measures of Damage Probability Matrices (DPM) have been derived from the qualitative and incomplete relative frequencies contained in the EMS-98 Scale for the six vulnerability classes (from A to F). Moreover, a useful simplified parametric representation of the corresponding sets of probability distributions of the damage is provided adopting a unique parameter independent from the macroseismic intensity, which can be recognised as a vulnerability index.
With reference to the building typologies defined in the EMS-98 scale, the associated Damage Probability Matrixes have been derived interpreting the correlation suggested by the scale with the vulnerability classes, in terms of relative frequencies of the classes. Bayes' theorem allows the upgrading of the frequencies when further data about the built-environment or specific properties of the buildings are available, allowing the identification of a different behaviour with respect to the one generally considered for the typology. Fuzzy measures of any damage function can be derived. For every result of the seismic analysis, the procedure allows supplying to the user the final uncertainty connected with the aforementioned uncertainties.
This macroseismic method can be employed on the basis of poor statistical existent data (such as ISTAT national census data) or information properly surveyed. Furthermore, it can be implemented both for the vulnerability assessment of single buildings and of built-up areas.
Implementations of the method are carried out for ordinary buildings in Sulmona (Italy) considering the 14th ISTAT national census data and the information collected building by building in a field survey. With reference to the ISTAT data, the interpretation of this base of information for the vulnerability assessment of buildings is presented.

KEYWORDS: Vulnerability assessment, Damage scenario, Macroseismic Intensity

1. INTRODUCTION

Definitive publication in 1998 of the new European Macroseismic Scale (Grunthal, 1998), stimulated the elaboration of new methodologies for the development of damage scenarios to the urban fabric (for earthquakes of predetermined intensity) or risk assessments in relation to the ascertained shakeability of the areas. In these methodologies, generally identified with the adjective "macroseismic" (Giovinazzi and Lagomarsino, 2004; Lagomarsino and Giovinazzi, 2006), the conventional vulnerability measures (the 6 vulnerability classes) and the damage grades are directly assumed from the scale, together with the list of the building typologies (possibly modified taking into account the local particularities).
The applications carried out are characterised by the different territorial scale (suburban, urban, municipal or regional) and by the different catalogues used for the systematic or sampled classification of the building typologies present in the territory. In particular, numerous applications are based on poor but systematic data

(for instance ISTAT national census data, a Italian nation-wide census of population and dwellings carried out every 10 years) possibly checked by sampling with richer and more reliable information (Bernardini, 2004).
The method proposed is derived making reference to the European Macroseismic Scale EMS-98 that implicitly contains a description of the Damage Probability Matrices (DPM) for each vulnerability class.
The use of observed damage data, suitably processed and organised in terms of DPM, has been introduced in Italy for the vulnerability analysis and forecast of the expected damage, starting from the Irpinia earthquake of 1980 (Braga et al., 1980). In particular, the DPM supply for a seismic input described in terms of macroseismic intensity and for the different building classes with homogeneous behaviour (vulnerability classes), the probability of occurrence of different damage grades to the building (defined on the basis of the damage observed in the structural and non structural elements).
In this paper, the macroseismic methodology proposed is outlined. Moreover, an implementation of the methodology to the ordinary buildings in Sulmona (Italy) is carried out using the 14th ISTAT (ISTAT, Italian National Institute of Statistics, 2001) census data.

2. DAMAGE PROBABILITY MATRICES DERIVED FROM THE EMS-98 SCALE

The EMS-98 scale supplies, for each macroseismic intensity, the probability of occurrence of the five damage grades D_k (k = 1 to 5), in terms of Damage Probability Matrices (DPM) for the six vulnerability classes (Bernardini et al., 2007). The vagueness of the adjectives (the frequency of expected damage is defined by few, many or most) and incompleteness of the information (for each class and intensity at most the frequency of two damage grades is characterised) does not, however, permit associating very precise numerical DPM to the vulnerability classes. For what concerns the first aspect, the scale suggests possible numerical values that can be associated with the three linguistic adjectives used to define the expected damage: Few, Many, Most.
In order to obtain the complete description of the DPM, a reasonable linguistic complement of the definitions supplied by the scale is performed, making first and foremost the “fuzzy pseudo-partition” (Klir and Yuan, 1995) of the interval [0, 100] of the percentages of buildings, directly deducible from the EMS-98, more coherent. The five “fuzzy sets” associated with the adjectives Nearly None, Few, Many, Most and Nearly All, defined under the condition that for each percentage the sum of the membership values is equal to 1, are shown in Figure 1.

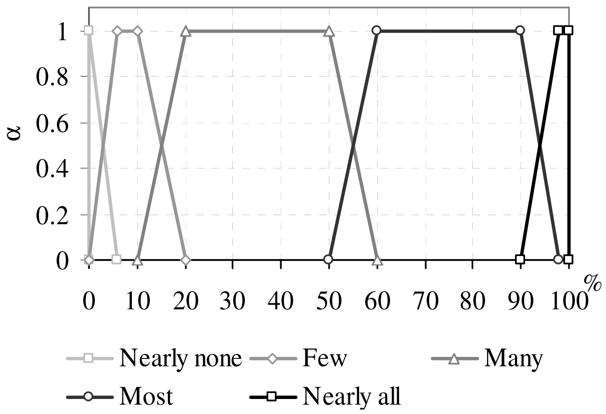

Figure 1. Proposal of a fuzzy pseudo-partition of the interval [0, 100] through 5 fuzzy sets associated with Nearly none, Few, Many, Most and Nearly All.

CLASS B						
I	D_0	D_1	D_2	D_3	D_4	D_5
V	All-Few	**Few**	None	None	None	None
VI	Many + 7/3Few	**Many**	**Few**	None	None	None
VII	7/3Few	Many	**Many**	**Few**	None	None
VIII	1/3Few	2Few	Many	**Many**	**Few**	None
IX	None	1/3Few	2Few	Many	**Many**	**Few**
X	None	None	1/3Few	2Few	Many+ Few	**Many**
XI	None	None	None	Nearly Few	8/3Few	**Most**
XII	None	None	None	None	None	**All**

Figure 2. Linguistic completion of the DPM related to class B.

With reference to the fuzzy pseudo-partition shown in Figure 1, the linguistic definitions contained in the scale were completed respecting two rules (Bernardini, 2004):
- the sum of “ expected white” (central value of percentage of the α-cut , with α = 0.5) damage distributions is equal to 100;
- by parity of class the increase of an intensity grade that is, by parity of intensity, the passage to the more vulnerable class produces a unitary increase of the damage grade.

Figure 2 shows the result of the linguistic completion of the EMS-98 scale for the Class B. This shows: 1) the linguistic values directly suggested by the scale (in bold), 2) the linguistic completions proposed.
The numerical interpretation of the linguistic result is now expressible according to the random set theory (Bernardini, 1999) and "imprecise probabilities" (Klir, 2005).
For each α-cut of the fuzzy sets associated with the linguistic definitions, the frequencies of the damage grades are measured by "interval probabilities", to which is associated a convex set of possible damage probability distributions. As an example, Figure 3 shows the interval probabilities corresponding to Class A and intensity VIII; the precise distributions corresponding to the average values of the "white" percentages are also shown and, for comparison, the binomial distribution elaborated from the damage from the Irpinia earthquake (Braga et al., 1980) for the same Class A.

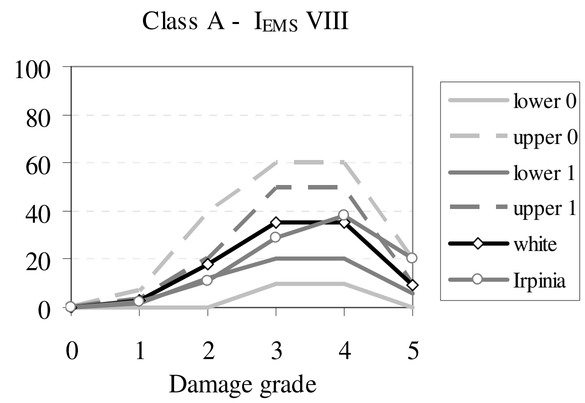

Figure 3. Class A, I_{EMS98} VIII: Interval probabilities for α-cut = 0 and 1 and "expected white" values compared to the Irpinia damage distribution.

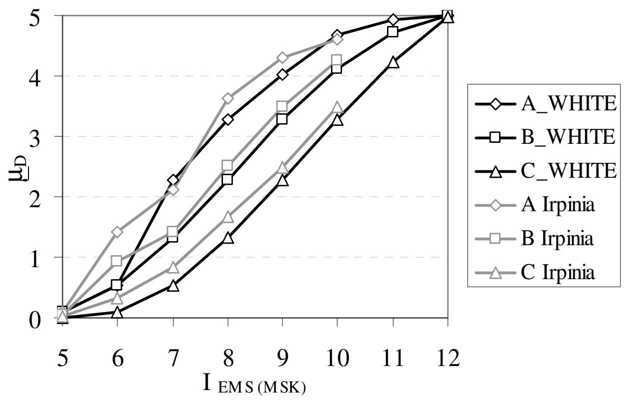

Figure 4. Comparison of the "expected white" values of damage distributions with the mean values of the Irpinia earthquake for the three classes A, B and C.

The damage distributions may be represented in terms of vulnerability curves, showing the value taken on by the averages of the distributions (μ_D) with variation of macroseismic intensity.
In Figure 4, the model of vulnerability deduced from the EMS-98 is compared to the damage distributions relative to the Irpinia earthquake. From the comparison, it clearly emerges how the trend of the two curve families is analogous and how there is a discrete correspondence between the three classes of DPM in Irpinia and the first three EMS-98 vulnerability classes.

3. PARAMETRIC REPRESENTATION OF THE DAMAGE PROBABILITY MATRICES

In order to obtain a more operative representation of the method, the Damage Probability Matrices derived from EMS-98 were parameterised with respect to a single parameter, that is the vulnerability index (V). It is worth pointing out that V does not depend on intensity and it is measured by a fuzzy set associated with each vulnerability class (Bernardini et al., 2007, Giovinazzi and Lagomarsino, 2004). In function of the parameter $V \in [0, 1]$, an analytic expression (Eq. 3.1), interpolating the numerical damage curves, was defined. The function proposed provides the mean damage grade μ_D as a function of the intensity I, only depending from the parameter V. Such a representation is shown in the following as a "parametric representation".

$$\mu_D = \left[2.5 + 3\tanh\left(\frac{I + 6.25V - 12.7}{3}\right)\right] \cdot f(V,I) \quad | \quad 0 \le \mu_D \le 5 \quad \text{where } f(V,I) = \begin{cases} e^{\frac{V}{2}\cdot(I-7)} & I \le 7 \\ 1 & I > 7 \end{cases} \tag{3.1}$$

The function f(V, I) is introduced to understand the trend of the numerical vulnerability curves taken from the EMS-98 even for the lower extremes of the intensity grades.
Figure 5 shows the comparison between the vulnerability curves relative to the numerical central "expected white" damage distributions and the parametric curves (Eq. 3.1) obtained for values of the vulnerability index shown in the label. These vulnerability indexes are the central "expected white" values of the fuzzy sets associated to each vulnerability class.

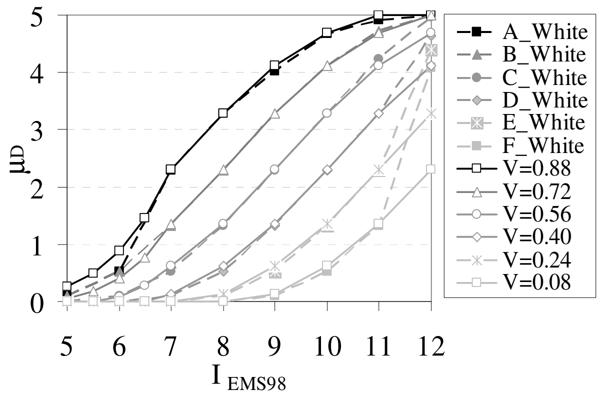

Figure 5. Curves I-μ_D corresponding to the central "expected white" values of the definitions of the scale for the 6 vulnerability classes and corresponding parametric vulnerability curves

It is interesting to note the perfect coherence between the two representations especially for the central grades of intensity, from I = VII to I = XI.

In order to describe the damage distributions (associated with each value of μ_D), a probabilistic distribution derived from the discretization of a beta distribution in the interval [0, 5] is adopted:

$$\text{PDF}: p_\beta(x) = \frac{\Gamma(t)}{\Gamma(r)\Gamma(t-r)} x^{r-1}(5-x)^{t-r-1} \tag{3.3}$$

where t and r are the parameters of the distribution, defined as a function of the average value μ_x and the variance σ_x^2 from Eq.3.4, and Γ the gamma function.

$$t = \frac{\mu_x(5-\mu_x)}{\sigma_x^2} - 1 \qquad r = t \cdot \frac{\mu_x}{5} \tag{3.4}$$

A discrete distribution also dependent on two parameters t and r may therefore be defined in the following form:

$$p(0) = P_\beta(0.5); \quad p(k) = P_\beta(k+0.5) - P_\beta(k-0.5); \quad p(5) = 1 - P_\beta(4.5)$$

$$\text{where } P_\beta(x) = \int_0^x \frac{\Gamma(t)}{\Gamma(r)\Gamma(t-r)} x^{r-1}(5-x)^{t-r-1} dx \tag{3.5}$$

The limited variation found in the values assumed by the parameter t for the numerical damage distributions taken from the EMS-98 allows one to assume a single value for t (equal to 8) as representative of the variance of all the possible damage distributions (Bernardini et al., 2007). Defining such a parameter a priori, it is thus possible to define the damage distributions exclusively through knowledge of the average value, but characterised by a variance coherent with that found from completion of the EMS-98 matrices.

4. VULNERABILITY TYPOLOGIES IN THE EMS-98 SCALE AND BEHAVIOUR MODIFIERS

With the aim of defining the DPM by building typologies the indications of the EMS-98 table of vulnerability were interpreted in terms of frequencies associated with the classes recognised as representative for each typology. The correlation between the 6 vulnerability classes and the typologies (of which 7 relative to masonry buildings and 6 to buildings in r.c.) are summarised in Table 1.

In almost all cases, one is not dealing with a deterministic relation, but with an implicit probabilistic relation of which a "modal" class is explicit, the "most likely vulnerability class" alongside two groups of classes judged "probable" and "less probable" or "exceptional".

An explicit reasonable hypothesis for interpretation of the above mentioned probabilistic relation is shown in Table 2: assuming for "less probable" the average "white" value of FEW (9%) and for "probable" the analogous value of 2.5*FEW (22.5 %), the modal frequency may be calculated for a difference at 100%. Furthermore, one assumes that in any case, the probability distribution takes on positive values in at least 3 classes, assigning to such a purpose a percentage equal to 4.5 (corresponding to the white value of FEW/2) to contiguous classes not envisaged by the EMS-98 and adding a class Y of buildings with greater vulnerability than that of class A.

Table 1. Correlation between vulnerability classes and typologies according to the EMS-98.

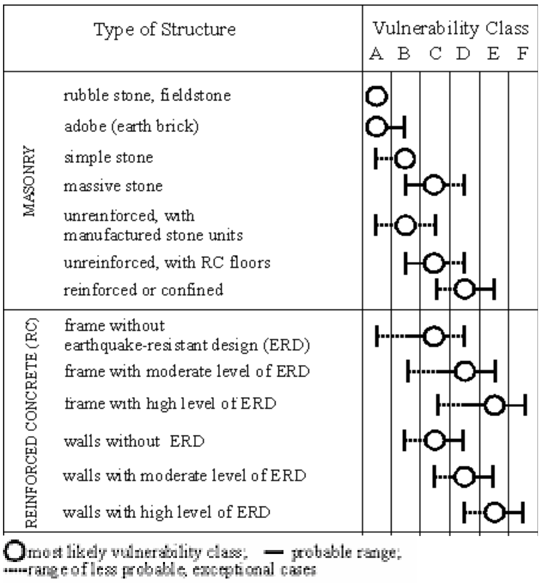

Table 2. Correlation between vulnerability classes and typologies according to the EMS-98 in terms of probability of the classes conditioned by typology.

Ti	*Vulnerability classes Cj*						
	Y	A	B	C	D	E	F
M1	4.5	91	4.5				
M2	4.5	73	22.5				
M3		9	86.5	4.5			
M4			22.5	68.5	9		
M5		9	82	9			
M6			22.5	68.5	9		
M7				9	68.5	22.5	
RC1		9	22.5	59.5	9		
RC2			9	22.5	46	22.5	
RC3				9	22.5	46	22.5
RC4			9	68.5	22.5		
RC5				9	68.5	22.5	
RC6					9	68.5	22.5

The percentages shown in Table 2 may be interpreted as probabilities of the classes Cj (j from 1 to 7) conditioned by typology Mi (i from 1 to 15):

$$m_j^{i,0} = \Pr\left(C_j \middle| M_i\right) \qquad \forall i : \sum_j m_j^{i,0} = 1 \tag{3.6}$$

On the basis of these assumptions, the DPM for EMS-98 buildings typologies can be easily defined.
The expected behaviour of "modified" building typologies due to the ascertained presence of specific factors or typological features (for instance the number of storeys) were then analysed, starting from the rather general building typologies defined by the scale. To this aim, a Bayesian procedure is proposed (Bernardini et al., 2007). The use of Bayes' theorem allows updating of the frequencies associated with the classes, in the case of availability of further data about the building that permit identification of modified behaviours compared to those envisaged for the typology. The Bayesian procedure is shown in the equation below:

$$\begin{aligned} m_j^{i,1} &= \frac{\Pr(C_j \cap S_{r_1})}{\Pr(S_{r_1})} = \frac{\Pr(S_{r_1}/C_j)}{\sum_l \Pr\left(S_{r_1}/C_l\right)\cdot m_l^{i,0}} m_j^{i,0} \\ m_j^{i,k} &= \frac{\Pr(C_j \cap \mathbf{S}_{r_k})}{\Pr(\mathbf{S}_{r_k})} = \frac{\Pr(C_j \cap (\mathbf{S}_{r_{k-1}}, S_{r_k}))}{\Pr(\mathbf{S}_{r_{k-1}}, S_{r_k})} = \frac{\Pr\left(S_{r_k}/C_j\right)}{\sum_l \Pr\left(S_{r_k}/C_l\right)\cdot m_l^{i,k-1}} m_j^{i,k-1} \end{aligned} \tag{3.7}$$

where $m_j^{i,k}$ are the probabilities of the classes Cj conditioned by sub-groups of the modified typology; S_{rk} are the the states $S_s = (S_{r1}, S_{r2}, \ldots S_{rm})$ respectively assumed by the modifiers. In general the k-th modifier (k from 1 to m) is a variable of state that may take on $r_k = 1$ to n_k values.
With reference for example to ISTAT 2001 data, the characteristics considered as vulnerability modifiers are: height of building, state of conservation, aggregation to other buildings.
Obviously the $\Pr(S_{rk}/C_j)$ are not known, they may however be supposed monotonically increasing or decreasing with the index j, depending on the expected effect of the modifier on vulnerability.
The application of more modifiers that systematically operate in the sense of increasing (or decreasing) vulnerability will progressively move the probability of the modal class to that more (or less) vulnerable, reducing or annulling the variance of the distribution. Vice versa, the application of non-homogeneous

modifiers from this point of view may substantially leave the modal class unchanged, but increase the variance of the distribution.

5. EXPECTED DAMAGE VALUES AND LOSSES

If one considers a generic real damage function f, measured by the 6 conventional grades of the EMS-98, from grade 0 (no damage) to damage 5 (structural collapse), it is possible to assess the expected value, for a fixed value of intensity I, both starting from the DPM directly derived from the scale and from analogous matrices parameterised by the vulnerability index V. In reality, taking into account the uncertainty with which the EMS-98 defines the implicit damage matrices, such a value may only be described by means of a fuzzy sub-set (Bernardini et al., 2007).

Starting from the DPM directly derived from the EMS-98, for each vulnerability class (Cj) and for each value of α-cut (of the fuzzy sets that measure the linguistic frequencies of damage), the frequencies associated with the damage grades are measured by "interval probabilities" (${}^{\alpha,j}IP$). This means therefore that in fact the DPM are not univocally determined even if one fixes the value of α: a convex set of DPM are possible and a corresponding interval ${}^{\alpha,j}Y$ of the expected value of the function f may be determined from the extreme values.

With reference to the matrices parameterised with the index V, each vulnerability class results associated with a fuzzy sub-set of the interval [0, 1] and thus, having a certain discrete number of α, ordinary intervals of said index V (${}^{\alpha,j}V$). Fixing the value of the macroseismic intensity, the two extreme DPM corresponding to the interval of variation of V and the consequent interval of the expected value of the function f of damage ${}^{\alpha,j}Y$ therefore turn out to be determined.

For each typology (index i) modified (index s) one now considers the random set (Bernardini, 1999), this also dependent on α, obtained by attributing the intervals ${}^{\alpha,j}Y$ with the probabilities $m_j^{i,s}$, independent of α. Thus it is possible to calculate the cumulative extreme functions of the random set and the interval of their expected values of the damage function considered (${}^{\alpha}Y_{i,s}$). It is also possible to calculate a specific "white expected" value ${}^{\alpha}Y_{i,s}^{white}$.

If the calculation is repeated for different values of α, one generates a fuzzy set that measures the expected value of the damage function for the modified typology, conditioned by the macroseismic intensity assumed. The barycentre of the fuzzy set is usable as the central "defuzzified" value for a central independent measure of the effective uncertainty of the DPM. One observes that a central defuzzified value may also be calculated with a direct calculation that uses the "expected white" DPM of each vulnerability class.

In summary, two different procedures to implement the vulnerability method are proposed: a) numerical procedure, based on the numerical DPM directly derived from the scale, b) parametric procedure, based on the matrices parameterised with the index V. The results of the comparison between the two procedures proposed (Bernardini et al., 2007) has shown small differences. It is worth highlighting that: on the one hand, the numerical procedure is considered as rigorous, since it is directly derived from the EMS-98 scale; on the other hand the parametric procedure has the advantage of an easy applicability even though it leads to making limited mistakes in comparison to the results of the numerical procedure.

6. APPLICATIONS TO SULMONA

The methodology described previously is applied to the town of Sulmona (Italy) to evaluate damages expected after an earthquake of fixed intensity.

The town of Sulmona (Figures 6, 7 and 8) is located in the heart of Abruzzo (Italy) in the Peglina Valley, on the slopes of the Maiella. The town of Roman origin, is essentially made up of a historical centre and two zones of expansion, with buildings built in the 1960s and 70s, to the south and north of the old nucleus. Sulmona has suffered numerous earthquakes of considerable intensity over the years. The most significant event that concerned the area was that of 1706 which produced considerable damage and was responsible for the current aspect of the historical centre. The last earthquake that affected the area was that of central Italy of 7th and 11th May 1984 ($I_{MCS} = 6.5$ in the centre of Sulmona) which provoked not serious but widespread damage throughout the centre.

Figure 6. Aerial photo of the historical centre of Sulmona

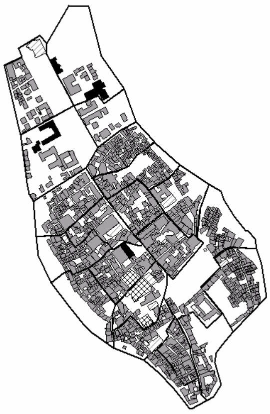

Figure 7. Map of the buildings within the census tracts

Figure 8. Buildings typologies in the historical centre

The methodology is applied to a group of 17 census tracts (Figure 7) chosen in the historical centre of Sulmona (Italy), with reference to the information deduced from 14th General Popolation Census and General Housing Census (ISTAT, 2001). The ISTAT data are collected in order to carry out a population survey and gather some information about dwelling characteristics. The ISTAT 2001 survey is performed for each census tract building by building; thus, the data collected by the 14th ISTAT census can be considered sufficiently reliable. As evidence of this, the comparison with the data collected on-site using a detailed survey form (Martinelli et al., 2008) shows a good agreement.

As for vulnerability purposes, the ISTAT 2001 catalogue, allows one to identify the building in terms of structural typology (masonry, reinforced concrete buildings with and without infill at ground floor, other), age of building (seven age ranges), height (number of floors), state of maintenance (excellent, good, common, and awful) aggregation conditions (isolated, adjacent with another building on one side or two or more side). A summary of the ISTAT data for the municipality of Sulmona is shown in Figure 9, 10 and 11.

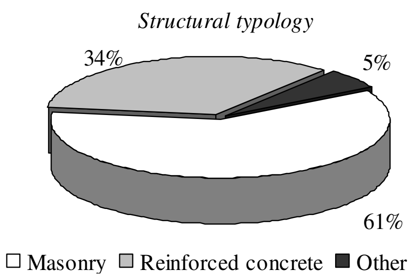

Figure 9. Structural typology

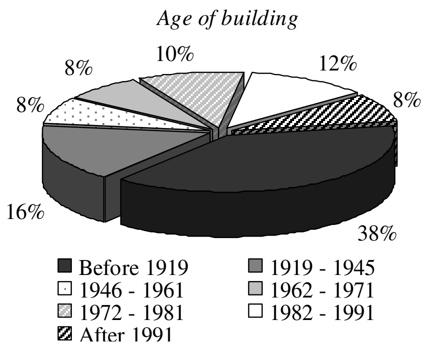

Figure 10. Age of building

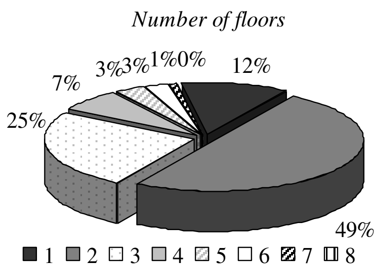

Figure 11. Number of floors

Structural typology and age class are useful in terms of characterization of the distribution in the EMS-98 building typologies in the territory (Table 3). Percentage of occurrence of the typologies in different ages of buildings was defined on the basis of the data survey collected on-site with a detailed survey form (Martinelli et al., 2008). Based on these appraisals, the characterization of the typologies was performed for the census tracts selected. In order to take into account the influence of the behaviour modifiers, for each recognized EMS-98 typology, the groups of buildings homogeneous by height, state of maintenance and aggregation conditions are then identified.

With reference to the parametric procedure, for each modified typology it is possible to define the interval of variation of the expected values (for each value of α) of the damage function chosen and the "white expected" value, having fixed the intensity. One considers, for instance, the damage function y = f (0,0,0,0.4,1,1) which defines the percentage of unusable buildings and a value of EMS-98 macro-intensity equal to VIII. Table 4 shows the expected values obtained for this damage function for a α value fixed to 0.5.

Table 3. Typology distribution in the census tracts chosen in Sulmona

Masonry EMS-98 typologies	Percentage of buildings
M1	38.7 %
M3	56.5 %
M4	4.7 %
Total	100.0 %

Table 4. Percentage of unusable buildings (α = 0.5) for I equal to VIII

Masonry EMS-98 typologies	Percentage of unusable buildings	
	min	max
M1	37.7 %	75.4 %
M3	9.8 %	38.4 %
M4	2.2 %	12.7 %

7. CONCLUSIONS

The methodology described confirms how the information contained in the EMS-98 scale, suitably interpreted, completed and re-elaborated may leading to a definition of Damage Probability Matrices, even if in an imprecise form. These matrices substantially make up an effective conventional definition of the Vulnerability Classes, usable therefore for a classification coherent with the EMS-98 of buildings.
The macroseismic method described here allows one to calculate in a manner coherent with the conventional definitions of damage grade and macroseismic intensity supplied by the EMS-98 scale expected values of any functions of seismic damage to populations of ordinary buildings, starting from systematic information, even very approximate, relative to buildings. In particular applications have been carried out on populations of buildings described by ISTAT 2001 data.

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