Vulnerability of masonry building types in Catania

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Abstract - A large scale evaluation of the seismic vulnerability of the overall stock of nearly 22000 masonry buildings in the town of Catania has been performed through the information on their geometrical and mechanical characteristics collected in the so called LSU database. Moreover 135 buildings have been particularly inspected and their seismic strength evaluated through a methodology based on the combination of simple mechanical models and experiential knowledge. Classification in three classes of vulnerability of the identified masonry types and probabilistic damage matrixes of past Italian earthquakes have been used to forecast damage scenarios for the reference earthquakes.

1. INTRODUCTION

In the years 1996-1998 the buildings of Catania have been surveyed in the ambit of the *Lavori Socialmente Utili* (LSU) Project. The activities, co-ordinated by the Italian Group for Seismic Protection (GNDT), have been planned to evaluate the seismic risk in the area, combining information on the vulnerability and on the expected ground motions. Particularly the high intensity earthquake in 1693 and the middle intensity earthquake in 1818 have been considered for the evaluation of damage scenarios in the town [1]. The present paper considers the vulnerability of masonry building stock, that is estimated to correspond to nearly 70% of the buildings and 50% of the total volume of the constructions. A preliminary vulnerability analysis on a more reduced database is reported in [2]. At the present time the data of about 15.000 masonry buildings are recorded in the database (Table 1). It is likely that the buildings registered by LSU project correspond to nearly 65% of the building stock.

Table 1: LSU-Catania Database

	Masonry buildings	R.C. buildings	Total
Records	15,326	7,319	22,639
Total (estimate)	22,500	10,500	33,000

The database identifies each building by means of 15 parameters of the "first level" GNDT form (typology of floors and walls; number of stories, maximum and minimum height, address, number of the group and number of the building; year of construction, following interventions, state of conservation of plasters and use) and furthermore 3 of the 11 parameters of "second level" GNDT form for masonry buildings (Connections of the structural elements, non-structural elements, maintenance).

A sample of about 135 masonry buildings of Catania has been selected and more precisely surveyed for vulnerability evaluations.

The LSU database itself gives important criteria which allow to improve the significance of the sample, preserving the relative frequency of walls and floors typologies, age and number of stories. Moreover, other available database of the historical town center have been used to represent as well as possible the overall population, because the LSU Database was only partially available at the time of sampling.

In Figures 1, 2 the sample is compared with the LSU database, from the point of view of the frequencies of number of stories and age of the building (year of construction). It must be noted that the sample of buildings is fairly older in comparison with the reality described by LSU database. On the contrary, the frequencies corresponding to the number of storeys are substantially similar, even if with a slight over-estimation in the sample of the highest buildings.

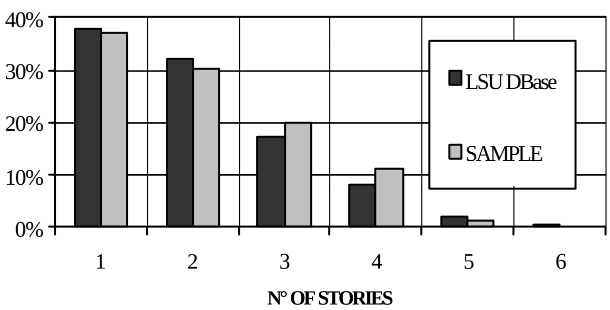


Figure 1 : Relative frequencies of number of stories in the of LSU – Database (13000 buildings) and in the observed sample (135 buildings)

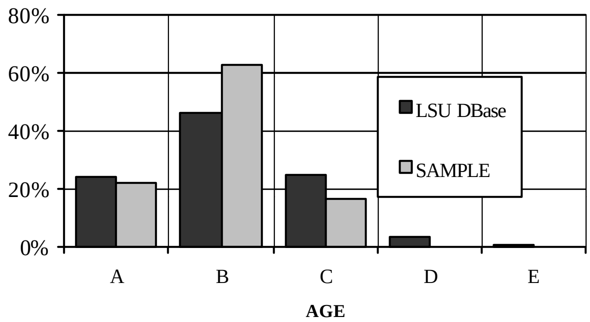


Figure 2 : Relative frequencies of construction age in LSU database and in the observed sample (A : <1919 ; B: 1919 – 1945 ; C: 1946 – 1960 ; D: 1961 – 1971 E: 1972 – 1975)

2. VULNERABILITY OF THE SAMPLE THROUGH THE VULNUS PROCEDURE

The VULNUS procedure [3] is based on a vulnerability model of masonry buildings, depending on the following parameters:

I_1 : ratio of in-plane shear strength of the walls system to total weight;

I_2 : ratio of out-of-plane flexural strength of the most critical external wall to total weight, evaluated summing the resistance of vertical (I2’) and horizontal (I2’’) strips;

I_3 : weighted sum of the scores of seven partial vulnerability factors;

A : mean absolute acceleration response of the building; Shaking table tests on masonry buildings models [4, 5] show that in the highly damaged state A is nearly equal to PGA.

a : uncertainty factor depending through a fuzzy relation from I3.

The output Vu = f(I1, I2, A, a) is the Probability of collapse or damage $\geq$ D4 (EMS98 : European Macro-seismic Scale 1998 [6]). The analysis can be performed for a building (Vu) or for a group of buildings (Vg).

From the obtained fuzzy sets upper bounds, lower bounds and mean “white probabilities” of the Cumulative PDF F(Vu) or F(Vg) , as well of the corresponding Expectations E[Vu] or E[Vg], can be calculated according to the Theory of Random Sets [7].

The numerical values assumed for the main mechanical parameters required by VULNUS analysis code for vertical and horizontal structures are reported respectively in

Tables 2 and 3. It must be observed that such values represent just reasonable hypotheses based on the experimental tests carried out by flat jacks technique [1] and similar tests carried out on Catania Cathedral [1] and also on tests described in Sciuto Patti, 1896 [8]. Nevertheless the uncertainties linked to such values are taken into account in the analysis model by means of the fuzzy representation of the vulnerability measures.

The choice of the values to be assumed for the active confinement forces on the walls, corresponding to the various floors typologies, results particularly difficult. In the case of plane floors they have been assumed substantially proportional to the vertical support reactions multiplied by friction coefficients varying between 0.3 and 0.6.

Table 2 : Average strengths and densities of masonry types in the sample

	LSU Code	Compression strength (MPa)	Tensile strength (MPa)	Specific density (kg/m^3)
Irregular fabric of rubble lavic stones	A, E	1.2	0.07	1800
Irregular fabric reinforced by transverse *cannarozzoni* and/or clay bricks .	B, F, C1	2	0.12	2000
Quasi-regular fabric of roughly hewn lavic stones with nearly horizontal mortar joints	C2, G1	3	0.20	2300
Quasi-regular fabric of roughly hewn lavic stones reinforced by layers of clay bricks	D	4	0.22	2200
Regular fabric of concrete blocks or calcareous *tufo* hewn stones	H, I, G2	4	0.20	1700

Table 3 : Average confinement forces and unit weight of floor types in the sample

	LSU Code	Confinement on walls orthogonal to the beam direction (kN/m)	Confinement on walls parallel to beam direction (kN/m)	Unit weight (kN/m^2)
padiglione vaults on thin shoulders, without chains	F1	- 1	- 1	3 - 4.5
padiglione or *crociera* vaults on thick shoulders, without chains	F2	0.5	0.5	3 – 6
Wood beams without chains	A	2	0.5	1.5 – 3
Steel beams and vaults	C	6	1	3 - 4.5
Solid or lighted r.c. slabs	E	20	10	3 - 6
Mixed vaults- plain floors	H	Average values weighted with their relative areas are assumed		
Floors with chains	I, B, D	The procedure evaluates separately the contribution of the chains in the two principal directions (15 kN each chain) for each building, and adds it to the forces corresponding to the various types.		

As it regards the vaults, the thrusting effect due to vertical loads should be taken into account, as well to the vertical components of acceleration, uniformly distributed on the boundary walls for *padiglione* vaults, substantially concentrated and absorbed by transverse walls for *crociera* vaults. This consideration could suggest assuming negative values of confinement forces. A careful observation of the geometry of Catania vaults made with *pomice*, almost semicircular, seems to suggest a substantial balancing of positive and negative effects on confinement, justifying then values close to 0.

3. CLASSIFICATIONS OF TYPES IN 3 VULNERABILITY CLASSES

A first classification of the buildings of Catania, significant for the analysis of seismic vulnerability, may be done by calculating, for each building, a parameter called "*Vulnerability Class*" of dominion (A, B, C), according to the rule of combination of the qualities of vertical and horizontal structures. The usual criterion of considering three classes of decreasing vulnerability in the macro-seismic MCS or MSK scale, as well as in the more recent EMS98, is assumed.

Table 4 : Hypothesis of classification of masonry buildings in three vulnerability classes

STRUCTURES	**Horizontal**	Vaults	Wooden floors	Mixed vaults / steel and vaults floors	Vaults or mixed vaults / floors with chains	Steel beams and vaults or tiles	Wooden floors with chains	Steel beams and vaults or tiles with chains	R.C. slabs
Vertical	LSU Code	F, F1, F2	A	H	G, I	C	B	D	E
Irregular fabric of rubble lavic stones, low or fair quality mortar	A,E	A	**A**	**A**	**A**	**A**	**A**	**A**	**A**
Irregular fabric reinforced by *cannarozzoni* and/or clay bricks, low or fair quality mortar	B, F, C1	**A**	**A**	**A**	**B**	**B**	**B**	**B**	**B**
Quasi-regular fabric or roughly hewn lavic stones with nearly horizontal mortar joints, low or fair quality mortar	C2, G1	**A**	**A**	**B**	**B**	**B**	**B**	**B**	**C**
Mixed walls of medium quality	T	A	**A**	**B**	**B**	**B**	**B**	**B**	**C**
Quasi-regular fabric or roughly hewn lavic stones reinforced by layers of clay bricks, fair quality mortar	D	**A**	**A**	**B**	**B**	**B**	**B**	**B**	**C**
Regular fabric of concrete blocks or calcareous tufo hewn stones, fair quality mortar	H, I, M, G2	**A**	A	**B**	**B**	**B**	**B**	**B**	**C**
Regular fabric of solid or low hollowed clay bricks, good quality mortar	L	**A**	**B**	**B**	**B**	**B**	**B**	**C**	**C**

The list ordered by decreasing vulnerability, shown in Table 4, is based on considerations concerning the walls resistance (according to data of Table 2) and further assumptions resumed in § 2; as regards the horizontal structures, the positive effect of confinement forces and of chains (when they are present), and the negative effect of dead load have been considered. The resulting classification is shown in Figure 3, where large differences of the relative frequencies in the LSU database and in the sample appear clearly. Figure 4, where an homogeneous comparison is shown for 81 buildings respectively as recorded in the LSU database and observed in the survey, suggests that the difference should be partially due to inconsistent registration of the structural types in LSU database, particularly for horizontal structures (the LSU teams generally did not observed the interior of the building, while the building of the sample was accurately and completely surveyed).

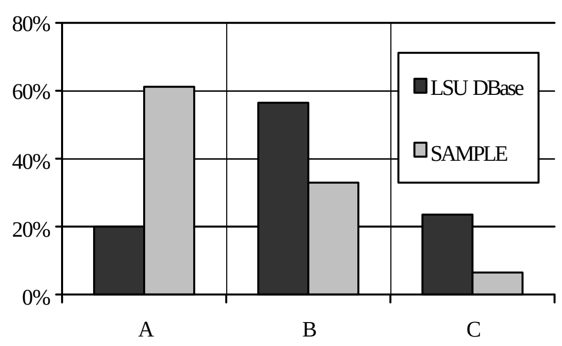


Figure 3 : Relative frequencies of Vulnerability classes in LSU database (13498 buildings) and in the observed sample (135 buildings).

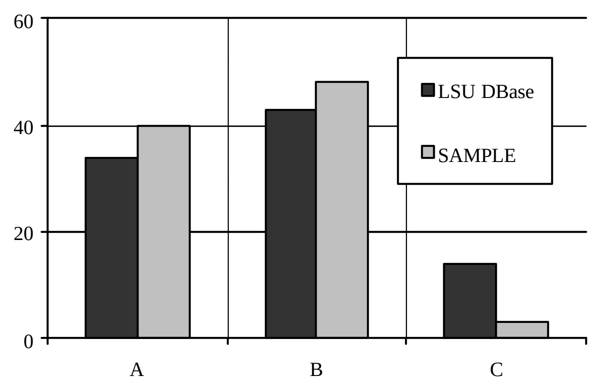


Figure 4 : Vulnerability Classes for a sample of 91 buildings, according to characteristics assumed by LSU teams and those actually observed.

4. VULNERABILITY ANALYSES

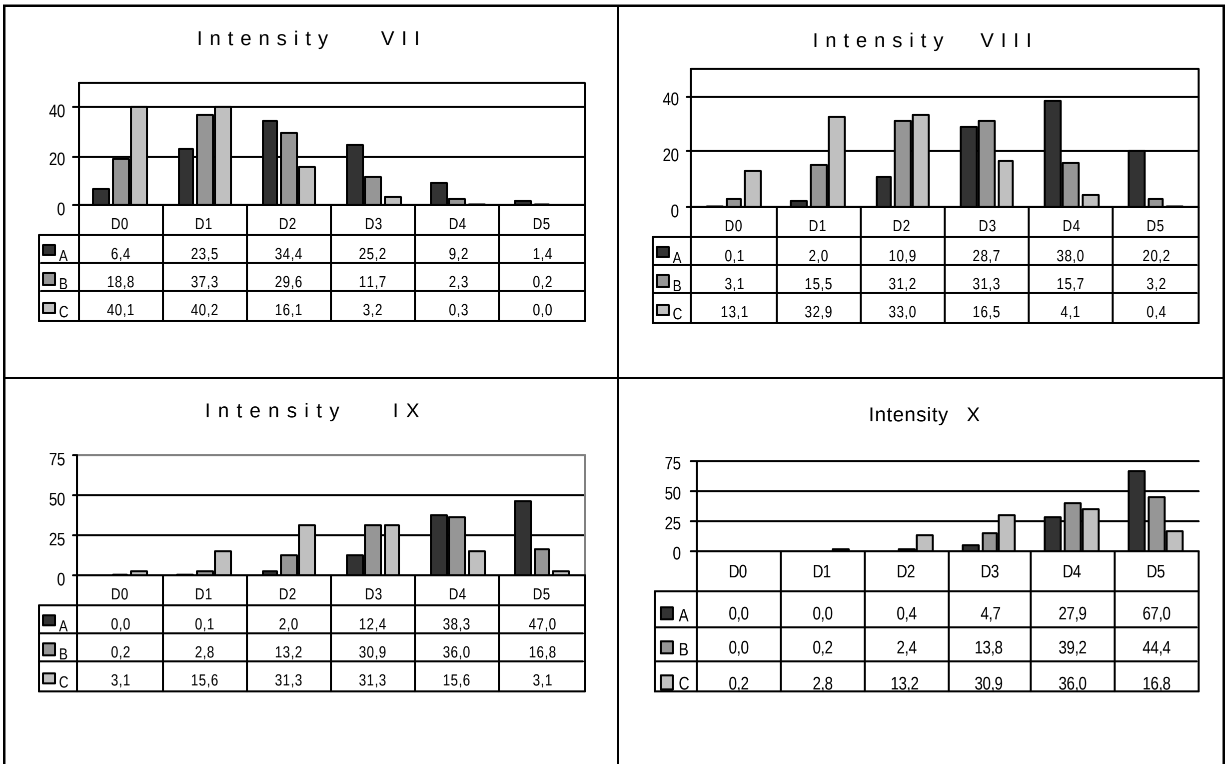
The expected vulnerability for the classes A, B and C in Catania has been evaluated by using the Damage Probability Matrices (DPM) calibrated on damages of Italian types surveyed after earthquake of different intensities in the period 1980-1995, but particularly the Irpinia earhquake, 1980 [9, 10]. The study has been carried out on the masonry buildings only, so as the aim of the present work (Figure 5). At the present time specific DPMs for the Catania area are not available and the comparison between the typological characteristic of the building structures of both the sites (Catania, Irpinia) put in evidence basic differences in the mechanical characteristics of the material used either in the vertical structures (harder volcanic stones and some good mortar in Catania against rough stones with worst mortar in Irpinia) or in the horizontal structures (vaults more diffuse in Catania and wooden floors in Irpinia). However the application of the proposed DPM is justified by the good agreement between the number of the storeys and the age of the buildings in both the sites so as by the behaviour of the masonry buildings without chains.

The expected vulnerability forecasted by VULNUS methodology, for the corresponding observed samples, is shown in Figs. 6 for the three above defined classes of buildings.

Comparison of the results of the two methodologies is possible assuming that Vg is the probability of damage $D \geq D_4$, the mean absolute acceleration response of the building in the damaged state is nearly equal to PGA [7] and the correlation between macro-seismic intensities and PGA (or better Equivalent PGA) values.

In fact uncertainty on this correlation is very high [11], and probably site dependent. A preliminary comparison has been performed using a correlation between MCS and PGA suggested in [12] on the basis of the macro-seismic local classifications and accelerograms recorded during the Irpinia and Abruzzo past Italian earthquakes.

The correlation between the two methodologies displayed in Fig. 6 is good for Vulnerability Class A: in this case for MCS intensities WIII and IX the DPM 2000 give probabilities of high damage or collapse well fitted to the central “Whi
suggested by VULNUS. For Class B and C (and also for Class A for low and high MCS intensities) the same probabilities are better fitted to the “Upper bound” of the expected vulnerability suggested by VULNUS.



Intensity VII

	D0	D1	D2	D3	D4	D5
A	6,4	23,5	34,4	25,2	9,2	1,4
B	18,8	37,3	29,6	11,7	2,3	0,2
C	40,1	40,2	16,1	3,2	0,3	0,0

Intensity VIII

	D0	D1	D2	D3	D4	D5
A	0,1	2,0	10,9	28,7	38,0	20,2
B	3,1	15,5	31,2	31,3	15,7	3,2
C	13,1	32,9	33,0	16,5	4,1	0,4

Intensity IX

	D0	D1	D2	D3	D4	D5
A	0,0	0,1	2,0	12,4	38,3	47,0
B	0,2	2,8	13,2	30,9	36,0	16,8
C	3,1	15,6	31,3	31,3	15,6	3,1

Intensity X

	D0	D1	D2	D3	D4	D5
A	0,0	0,0	0,4	4,7	27,9	67,0
B	0,0	0,2	2,4	13,8	39,2	44,4
C	0,2	2,8	13,2	30,9	36,0	16,8

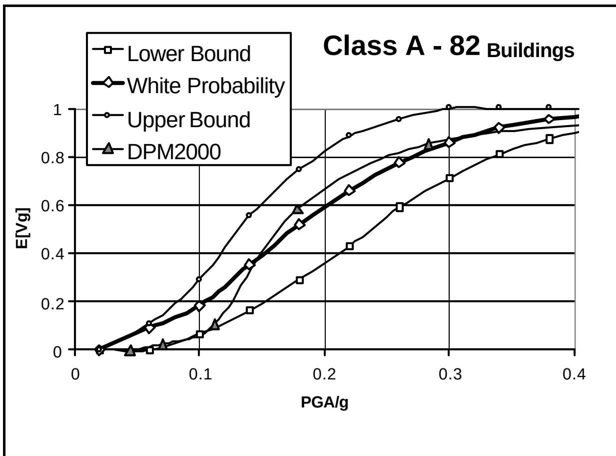
Figure 5 : Percentage distribution of damage for MCS intensities VI to X [10]
(D0: no damage; D1: slight; D2:moderate; D3: substantial to heavy; D4:Very Heavy; D5: Destruction

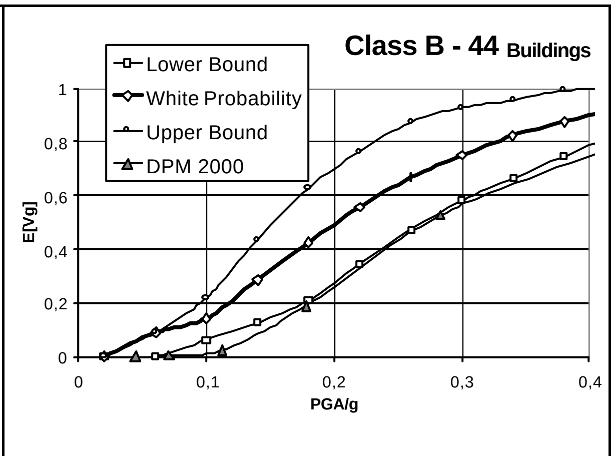
A preliminary damage scenario for the masonry buildings of Catania can be derived by Figs. 6, taking into account the distributions of Vulnerability Classes A, B, C in Figs. 3 and 4 and data suggested for PGA in the different sections of the towns [1]. For the high intensity earthquake in 1693 and the middle intensity earthquake in 1818 PGA are respectively in the ranges [0.22, 0.35] and [0.14, 0.28], corresponding to MCS IX-X and VIII-IX, according to the assumed correlation.

5. DISCUSSION AND CONCLUSION

Preliminary estimates based of expected damages of the masonry buildings stock have been evaluated through classification of the buildings in three classes of increasing vulnerability and two independent methodologies based respectively on statistically evaluated Irpinia DPM and VULNUS procedure. Both the methods confirm a very high percentage (from 60 to 90%) of collapsed or heavily damaged (in any case unusable in the post-event emergency) buildings for an earthquake of the intensity recorded in 1693 in the town of Catania. Moreover a considerable percentage of highly damaged buildings (from 20 to 60%) can be forecasted for the lower intensity earthquake recorded in 1818. These surprising and worrying conclusions, particularly for the middle intensity reference earthquake, seem suggest stronger damage scenarios than previously expected: therefore their reliability should be more extensively inquired, taking into account the uncertainties above underlined.

Particularly further research is required to confirm the assumed statistical distributions of masonry types and, above all, the correlation between MCS intensities and PGA, or better to an equivalent PGA, to take into account duration and frequency content of the ground motion.





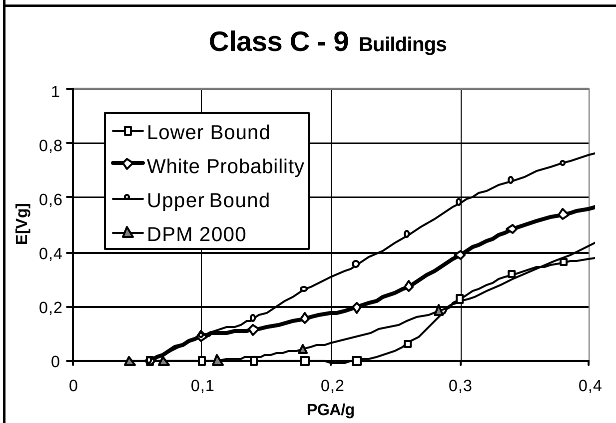


Figure 6 : Bounds and central ("White") value of the expected vulnerability according to VULNUS procedure and probabilities of Damage ≥ D4 according to DPM 2000 [10] , as a function of PGA, for the three assumed classes of buildings. The correlation suggested in [12] between MCS intensities from V to IX and PGA has been assumed. The mean absolute acceleration response of the building has been assumed equal to PGA [7]

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