Appendix: VULNERABILITY ASSESSMENT FROM QUICK SURVEY DATA IN THE HISTORIC CENTRE OF CATANIA

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Foreword

The data needed for the vulnerability assessment of residential buildings in Catania have been gathered in the field using simplified forms, through an extensive and quick survey.

The simplified forms were obtained from the classical GNDT 1st and 2nd level (Benedetti and Petrini, 1984) forms that were used in this project for public buildings (GNDT 1996 version). Two simplified forms have been set up, one for masonry the other for R/C buildings, and containing 19 and 17 entries respectively.

An overall damage assessment is carried out in an indirect way (Benedetti and Petrini, 1984): first a vulnerability index is determined on the basis of the data gathered from the survey, then a relationship is used among vulnerability index, expected damage and horizontal peak ground acceleration (Guagenti and Petrini, 1989).

In the following paragraphs a brief description is given of the simplified form, of the methodology used for the vulnerability assessment and of the ensuing results.

A.1 Masonry buildings

A.1.1 *Vulnerability parameters*

In order to assess the vulnerability of structures, the standard procedure for the 2nd level GNDT form was used (GNDT 1986 version). To adapt the data to this procedure the values of 8 parameters were generated as follows (see Table A.1):

- parameters 4 (location and soil condition), 6 (plan shape), 7 (regularity in elevation) and 8 (distance between walls) of the 2nd level form were obtained from the general knowledge provided by local experts: two values have been considered for each of them, as reasonable lower and upper bounds of the distribution (indicated as case A and case B);
- parameters 2 (resisting system quality), 3 (conventional seismic strength), 5 (floor effectiveness), 9 (roof) have been deduced by correlation with 1st level data.

Each parameter has been used to select a vulnerability class associated to it. Four classes have been used in increasing order of vulnerability from A to D. The complete list of the rules used is summarised in Table A.1.

A weight ‘p’ is assigned to each vulnerability parameter, ranging from 0.25 for the less important parameters up to 1.5 for the most important ones (Conventional seismic strength).

Table A.1: Vulnerability parameters and classes

GNDT FORM PARAMETER	INFORMATION GATHERED	RULES TO SELECT THE VULNERABILITY CLASS
1 – RESISTING SYSTEM TYPE	Quick form (field 16)	Direct, in case of absence class = C
2 – RESISTING SYSTEM QUALITY	Quick form fields 12 & 13: vertical structures, horizontal struct.s	A: M2OR (see structural type in Fig.A.4) B: M2OD C: M1OR, M2OR, MXVX, other D: M1OD
3 – CONVENTIONAL SEISMIC STRENGTH $C_{conv} = H_u/W$	Local experts + Structural type + preservation state +statistical evaluation	A: $C_{conv} \geq 0.4$ B: $0.24 \leq C_{conv} \leq 0.4$ C: $0.16 \leq C_{conv} \leq 0.24$ D: $C_{conv} \leq 0.16$
4 – LOCATION AND SOIL CONDITION	Local experts + upper &lower limit	Class B as lower vulnerability case Class C as upper vulnerability case
5 – HORIZONTAL STRUCTURES	Fields 13 and 14	A: fields 13 and 14 ≠ A,C,F,G,H B: field 13 ≠ A,C,F,G,H &field 14 =A,C,F,G,H C: field 13 = A,C,F,G,H & 14 ≠ A,C,F,G,H or other conditions D: field 13 and 14 = A,C,F,G,H
6 – PLAN SHAPE	Local experts + upper &lower limit	Class B as lower vulnerability case Class C as upper vulnerability case

7 – REGULARITY IN ELEVATION	Field 4 + statistical analysis	Based on maximum difference between the floor numbers of buildings in a block 'n':
		lower vuln. case: classes A, B or C if n=0,1,>1;
		upper vuln. case: classes B, C or D if n=0,1,>1;

8 – MAXIMUM DISTANCE BETWEEN WALLS	Local experts + statistical analysis + upper & lower l.	Class A as lower vulnerability case Class B as upper vulnerability case
9 - ROOF	Field 15	Class A: field 15 = P Class B: field 15 = O,R,T Class C: field 15 = N Class D: field 15 = M,Q,S
10 – NON STRUCTURAL ELEMENTS	Field 17	A,B: non structural elements absent or at very low risk (well connected, small, light) C: limited risk non structural elements, D: high risk non structural elements (badly connected, large, heavy, badly preserved)
11 – PRESERVATION STATE	Field 18	A: good condition, no visible cracks B: light cracks not due to earthquake C: medium cracks or reduction of masonry strength due to bad preservation of walls D: heavy damage (cracks or deformations or material degradation),

The quick survey form was obtained by using the parameters listed in Table A.2: most of them were selected from the 1st level GNDT vulnerability form (fields 1 to 15), while only three were chosen among the significant and easily detectable parameters of the 2nd level form (fields 16 to 18).

Table A.2: parameters used in the quick survey form

Field	Field name	Corresponding fields of GNDT form	CONTENTS AND CODES
1	N. aggregato	[34-37]	ID number of the block
2	N. edificio	[38:39]	ID number of the building in the block
3	N. civico	[56:59]	House number
4	N. piani	[85...]	Number of floors
5	H max	[98-100]	Maximum height above ground
6	H min	[101-103]	Minimum height above ground
7	Uso	[112] [122] [123]	Building use (residential, production, services)
8	Età	[270]	Building age (before 1919, 19-45, 46-60, 61-71, 72-75, 76-80, after 1980)
9	Interventi successivi	[272]	Subsequent intervention (0=none, 1=enlargment, 2=superimposed floor, 3=civil works, 4=restoration, 5=maintenance, 6=seismic repair, 7=seismic retrofit.
10	Stato intonaci	[273]	Plaster condition (E = effective, N = not effective, Z= not present)
11	Tipologia prevalente	[280]	Structural type (1 = special (churches, warehouse,..), 2=masonry or mixed, 3 = reinforced concrete, 4 = steel, 5 = other
12	Strutture verticali	[281...]	Vertical structure type: codes from A to V according to materials and texture
13	Orizzontamen-ti prevalenti	[283...]	Prevailing horizontal structure type: codes from A to L according to material and typology.
14	Altri orizzont.	[287...]	Other horizontal structures: codes as above.
15	Coperture prevalenti	[281]	Prevailing roof structure: codes from M to U, according to the typology, material and thrust.
16	Collegamenti strutturali	Parameter 1	Connections between structural elements: codes from A to D according to type, condition and code compliance.
17	Elementi non strutturali	Par. 10	Non structural elements
18	Stato di fatto	Par. 11	Building condition
19	Note		Essentially historic interest of the building (Y/N)

A.1.2 *Vulnerability*

A score 'C_v' is assigned to each vulnerability class of each parameter: from 0 (Class A – very low vulnerability) to 45 (Class D, high vulnerability). Most of the intermediate scores have values equal to 5 and 25 for classes B and C.

The building vulnerability index 'V' is calculated as the weighted sum of the vulnerability scores of the various elements:

$$V=\sum_{i=1}^{11} C_{v,i}\, p_i$$

The range of variation of V is between 0 and 382.5, but the values obtained by the weighted sum are finally divided by 3.825 to obtain a normalised range of variation 0 < V < 100. The vulnerability index is used as an intermediate step to estimate the damage to the building under a specified seismic action. The method was developed by Petrini (1993) and gives the expected damage as a function of the horizontal ground acceleration and of the vulnerability index.

The damage is expressed in a normalized scale (0< d < 1) and represents the cost necessary to recover the undamaged condition referred to the actual value of the building. High d values (0.8 – 1) are considered as equivalent to building collapse. For simplicity damage curves have a tri–linear shape defined by two points: the acceleration at which damage begins (d>0) and the acceleration at which the building is completely collapsed (d=1).

In Figure A.1 the damage curves for several values of the vulnerability index are plotted as a function of the peak ground acceleration coefficient a/g.

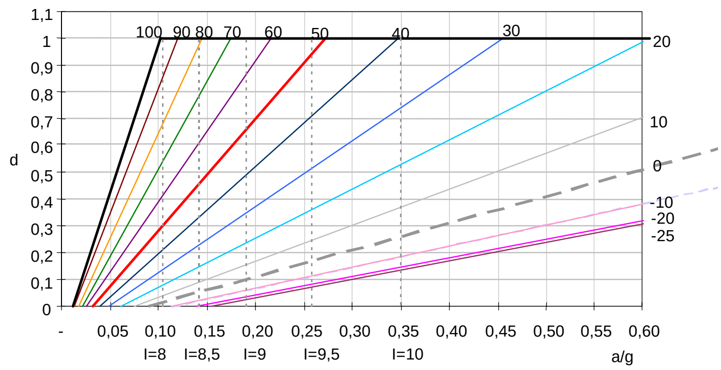

Figure A.1 **-** *Damage index vs. peak ground acceleration for some vulnerability index values*

A.1.3 *Results*

12.503 masonry buildings of the Catania city centre were surveyed asof this writing (November 1999). Some of their features drawn from the data are represented in Figures. A.2 to A.4.

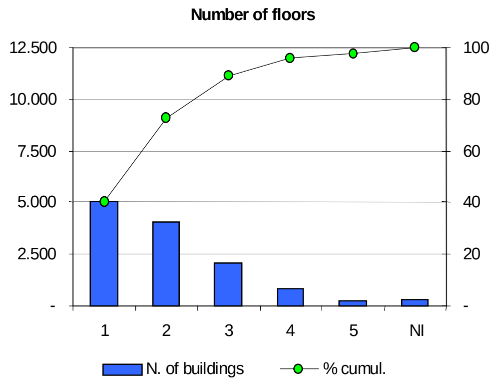

Figure A.2 - Number of floors: frequency distribution

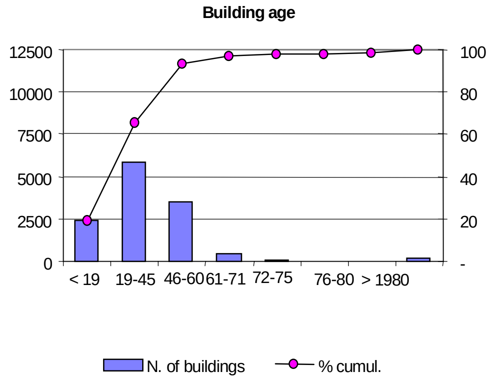

Figure A.3 - Building age: frequency distribution

STRUCTURAL TYPES

M1OD	Bad quality masonry with flexible floors
M1OR	Bad quality Masonry with rigid floors
M2OD	Good quality masonry with flexible floors
M2OR	Good quality masonry with rigid floors
MSOD	Mixed structures with flexible floors
MSOR	Mixed structures with rigid floors

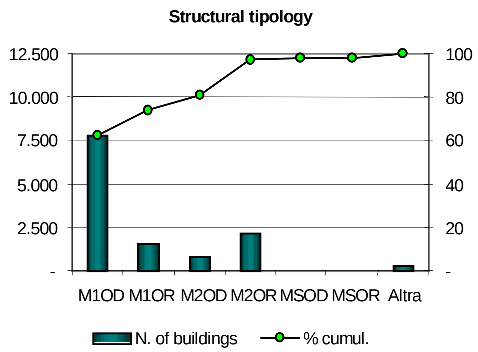

Figure A.4 - Structural types: frequency distribution

The vulnerability index was calculated with the previously described procedure for 12.309 surveyed masonry buildings and its distribution is given in Figure A.5. Two curves are shown: the first one correspond to the assumption that all the unknown vulnerability parameters have simultaneously the most favourable value (case A), while the second curve correspond to the opposite assumption.

The mean value of V is 31 in the first case (A) and 42 in the second case (B). Both values are consistent with the results obtained in other surveys (Petrini 1995), but the first one seems to be optimistic. Also the distribution obtained shows, in case A, relatively high frequencies in the low vulnerability range, which was not observed in other cases. An intermediate distribution between cases A and B seems to be reasonable.

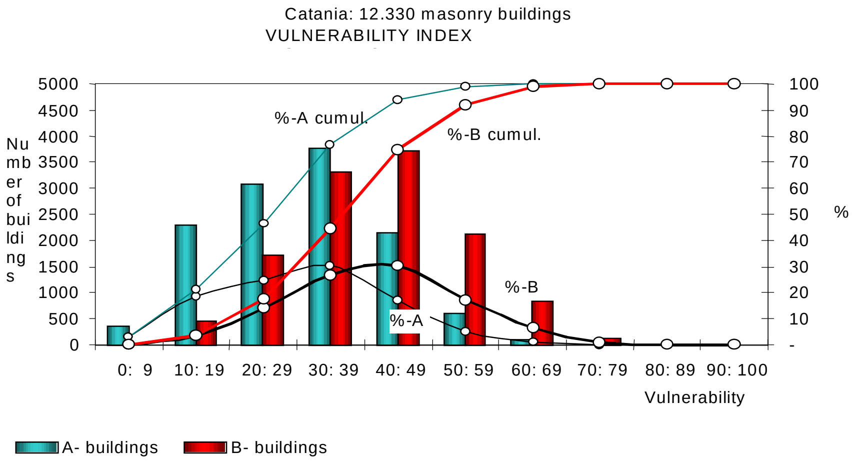

Figure A.5 - Distribution of the vulnerability index

The expected damage distribution in the surveyed area can be easily evaluated once the severity of ground shaking is fixed. In the following tables and figures some of these distributions are reported, in which the ground shaking is described both in terms of peak ground acceleration and of macroseismic intensity (MCS scale), the relationship between these variables being based on a correlation developed by Guagenti and Petrini (1989).

It can be easily seen from Fig. A.6 that when increasing the intensity from 0.25 to by ½ degree in the macroseismic scale, the damage distribution changes very much. In particular the percentage of collapsed buildings (d>0.8) rises from 15 % to 43 % in the lower bound of the parameters, while it rises up to 74 % if the upper bound of the unknown vulnerability parameters are used. This range of variation is probably excessive, but we must remind that is consequent to the simultaneous assumption of the best and worst values for all the unknown parameters. Also in this case a mean value between A and B cases seems to be the most reasonable choice.

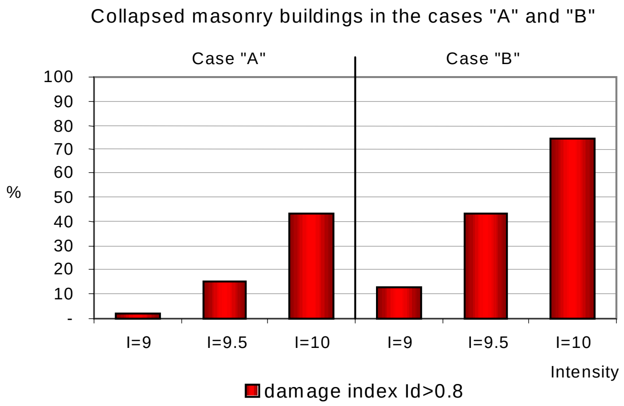

Figure A.6: Percentage of collapsed buildings Vs. Intensity in the two cases A and B

A.2 Reinforced concrete buildings

Reinforced concrete buildings were surveyed using a form which similar to the 2nd level GNDT form, though some parameters were summarised in variables which have a direct mechanical meaning. The vulnerability model was calibrated on the observed damage data of the Irpinia 1980 Earthquake, to get a good correlation between vulnerability index and damage, using a completely new approach.

The type of data gathered with the simplified form used in Catania are reported in Table A.3. Also in this case the corresponding fields of the ‘classical’ GNDT form are indicated.

A discrete scale with 8 damage levels, from 0 (no damage) to 7 (collapse), was used in the survey. In the subsequent elaboration, following Braga et al. (1982), the intermediate 1–4 damage levels were grouped into two levels obtaining a 6 level scale (0 to 5) similar to the MSK scale and to the damage scale used in the GNDT forms.

A.2.1 *Basic assumptions*

The basic assumptions are:

- damage is correlated to ground acceleration trough a tri-linear relation whose parameters are a function of the value of the vulnerability index; the relation is deterministic, so that the uncertainty on damage is only due to the uncertainty of the vulnerability index;
- macroseismic intensity (MCS) and peak ground acceleration are correlated trough the relationship proposed by Guagenti and Petrini (1989);
- the vulnerability model can be calibrated by means of the comparison with the damage observed after the destructive 1980 earthquake in Southern Italy, assuming that the r.c. building sample surveyed in that occasion belongs to a medium – high vulnerability range;
- the discrete damage scale used in the survey and the continuous scale used in the Petrini et al (1993) model are linearly correlated: damage level 0 correspond to damage index 0, damage level 5 (collapse) corresponds to damage index 1 (total loss of value of the building), intermediate levels are equally spaced (lev. 1 <-> 0.2, level 2 <-> 0.4, level 3 <->0.6, level4 <->0.8);
- the reinforced concrete buildings sample of Irpinia 1980 represents the mean situation of the inventory: each building moves away from it due to favourable or unfavourable characteristics gathered during the survey (seismic resistant design, soft story, large spans etc.).
- The favourable or unfavourable characteristics produce the final vulnerability index distribution of the Catania building sample, which can be different from the Irpinia one.

Table A.3: parameters used in the quick survey form.

Field	Field name	Corresponding fields of GNDT form	CONTENTS AND CODES
1	N. aggregato	[34:37]	ID number of the block
2	N.edificio	[38:39]	ID number of the building in the block
3	N. civico	[56:59]	House number
4	N. piani	[85..]	Number of floors
5	H 1° livello	[83]	Height of the 1^{st} floor
6	H max	[98-100]	Maximum height above ground
7	H min	[101-103]	Minimum height above ground
8	Uso	[112] [122] [123]	Building use (residential, production, services)
9	Età	[270]	Building age (before 1919, 19-45, 46-60, 61-71, 72-75, 76-80, after 1980)
10	Strutture verticali prevalenti	[281…]	Prevailing vertical structures (O = r.c. walls, P = bare r.c. frames, Q = r.c. frames with weak infills, R= r.c. frames with strong infills, U, V = other)
11	Sistema resistente		A: Walls or infilled frames with strong infills B: Frames with high depth beams and weak infills C: Frames with low depth beams & weak or no infills D: Frames with only external high depth beams, weak or no infills E: Frames with high depth beams and r.c. cores/walls
12	Maglia strutturale		Mean column span ≤ 4.5 m CLASS A Mean column span> 4.5 and ≤ 6.0 m CLASS B Mean column span > 6.0 m CLASS C
13	Dimensione media pilastri 1° livello		A: d ≤ 25 cm B: 25 < d ≤ 40 cm D: d>40 cm d= 1^{st} floor columns' mean transversal section dimension
14	Regolarità in pianta		A: Compact and regular (B/L < 2.5, e/B < 0.2); C: Irregular (B/L > 5, e/B >0.4); B: Intermediate cases
15	Tipologia tamponature 1° livello		A: Same kind of partitions at each elevation B: One floor weak and the others strong or one floor without partitions and the others weak C: One floor without partitions and the others with strong part.
16	Elementi tozzi		Short columns: A: H/d > 2:1 B: H/d < 1:2 C: H/d < 1:4
17	Note/Bow win		Essentially historic interest of the building (Y/N)

A.2.2 *Procedure*

The starting point is the evaluation of a vulnerability index distribution that can satisfactorily reproduce the damage observed after the Irpinia ’80 earthquake. The subsequent step is the choice of suitable rules that correlate the surveyed parameters of the Catania sample to the variation of the vulnerability distribution.

The first step is carried out as follows:

- The r.c. damage data of the Irpina ’80 earthquake are grouped according to the MCS intensity for which a significant sample is available (from I=V to I=IX-X excluding I=IX);
- For each MCS intensity the corresponding peak ground acceleration is estimated;
- The vulnerability values corresponding to damage levels 0, 0.2, 0.4, 0.6, 0.8 and 1 are determined from the damage curves (similiar to those in Fig. A.1) at the PGA values corresponding to the MCS intensities;
- A lognormal distribution is selected to describe the resulting frequency distribution of vulnerability;
- The damage frequencies observed in Irpinia for each MCS intensity are associated to the values of the vulnerability index determined in the previous step, obtaining discretized distributions of the vulnerability index, one for each Intensity (PGA); these distributions, in principle, would be identical if the various building samples were similar and the PGA – Intensity correspondence were perfect.

The different distributions obtained are compared and a single best-fitting lognormal distribution is selected; in this comparison the extreme points of the distributions are excluded because the presence of finite deterministic limits for the initiation of damage and for collapse is not consistent with the experimental values; the best fit lognormal function has mean value 12 and standard deviation 23.5.

At this point two key assumptions are made:

1. the mean of the lognormal distribution obtained is also representative of the r.c. buildings of Catania having average features (see Table A.4), as they were surveyed;
2. the vulnerability index of each r.c. building in Catania can be evaluated on the basis of how much its features are different from the “average” ones.

The surveyed features considered for vulnerability assessment are:

a. age of construction;
b. resisting structure;
c. mean column spacing ”i”;
d. mean dimension of the columns’ transversal section at the lowest level “d”;
e. number of floors “n”;
f. soft 1st storey;
g. presence of short columns;
h. regularity;
i. presence of non structural “bow – windows”.

Parameters c, d and e have been combined in a unique quantity σ, which gives the average normal stress under vertical loads in the 1st storey columns:

$$\sigma = q\, i^2\, n / d^2$$

where q is the average load per unit floor area.

A weight (p_i) has been assigned to each parameter to quantify its influence on seismic vulnerability. Each parameter range has been subdivided into three contiguous classes, namely low, medium and high vulnerability class.

In the following Table A.4. the weights of the parameters and the selection of the vulnerability classes are shown.

Table A.4: Surveyed parameters: weights and vulnerability classes

	Parameter	Importance	Weight	Vulnerability class		
			(p_i)	Low	Medium	High
1	Age	High	3	G (>1981)	F (46-81)	A,B,C,D,E (<45)
2	Resisting structure	High	3	A,E	B	C,D
3	Mean column normal stress	High	3	$\sigma \leq 4$ MPa	$4 < \sigma \leq 8$	$\sigma > 8$ MPa
4	Weak 1st floor	High	3	-	A	B,C
5	Regularity	High	3	A	B	C
6	Presence of short columns	Medium	-	-	A,B,C	-
7	Presence of non structural "bow – windows".	Low	1	-	A: information not available	B,C

The vulnerability index is estimated by means of a linear combination of the mean value of the distribution and of the variations DV^+ and DV^-

$$V = Vm + \Sigma_i\, k_i\, DV^+ \qquad \text{if } \Sigma_i\, k_i \geq 0$$
$$V = Vm + \Sigma_i\, k_i\, DV^+ \qquad \text{if } \Sigma_i\, k_i < 0$$

where:

Vm = 12 is the mean value of the vulnerability index,
DV^+ and DV^- define the range of variability of V, and are chosen so that $-25<V<100$.

Actually, it never happens that all the 7 parameters considered reach their maximum or minimum values, so the range of variability of V is smaller.

The combination coefficients k_i are obtained from Table A.4, satisfying the relationship $k_i = p_i/\Sigma_j p_j$, their maximum value being unity. In Table A.5 the K_i values are reported as a function of the parameter importance and of the vulnerability class.

Table A.5: K_i coefficients

	Vulnerability class		
Importance	Low	Medium	High
High	-1/4	0	3/16
Medium	-	0	-
Low	-	0	1/16

A.2.3 *Results*

In Figures A.7 and A.8 the frequency distributions of the number of stories and of the resisting system types are illustrated.

The vulnerability index was calculated by using the previous procedure for the 6.494 surveyed r.c. buildings. In Figure A.9 the vulnerability index distribution determined with the criteria given in the previous paragraph is reported. The mean value of V is 16 and the standard deviation is 22. Both values are slightly higher than the Irpinia sample, but this could be explained also by the fact that Catania has been officially classified as a seismic zone only since 1981, and has taller buildings than in Irpinia, often designed with low safety margins (more than 40 % of buildings have σ > 8 Mpa) .

Also in this case some overall damage estimations for specified intensities have been performed and are shown in Table A.6 and in Figure A.10.

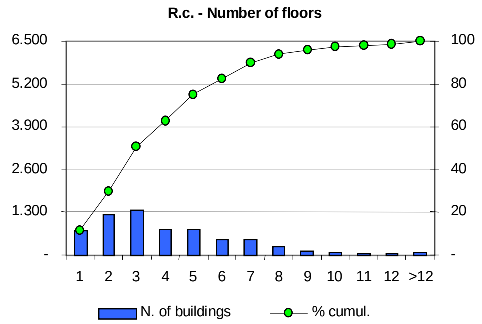

Figure A.7 - R.C. buildings: number of story frequency distribution

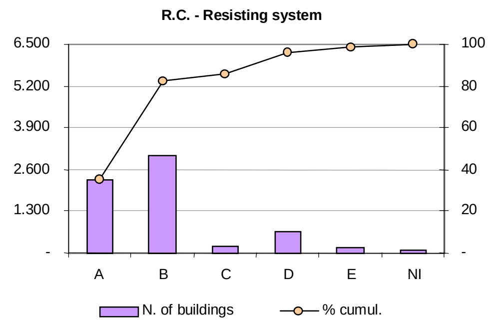

Figure A.8 - R.C. buildings: resisting system type frequency distribution

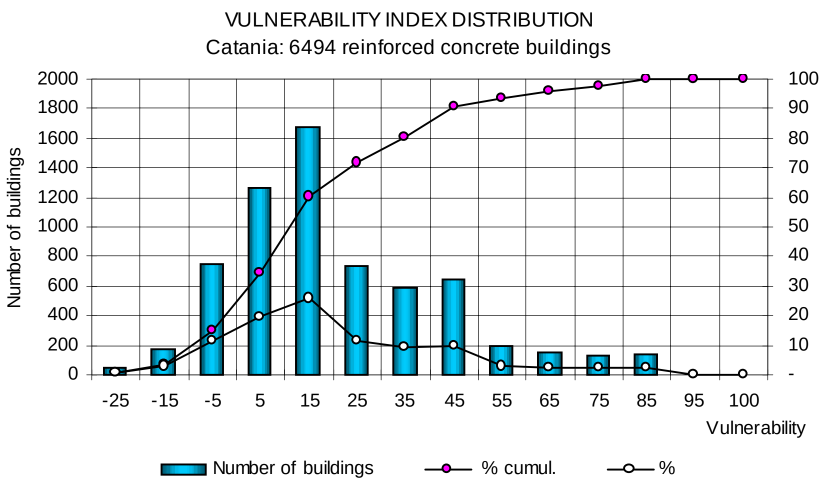

Figure A.9 **-** *Vulnerability index distribution for r.c. buildings in Catania*

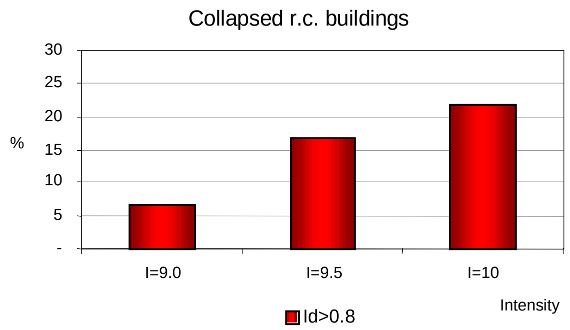

Figure A.10 **-** *Expected number of collapsed buildings vs. Intensity*

Table A.6: R.c. buildings: distribution of damage index

	I=8		**I=8.5**		**I=9**		**I=9.5**		**I=10**	
Id	**Freq.**	**%**	**Freq.**	**%**	**Freq.**	**%**	**Freq.**	**%**	**Freq.**	**%**
0	1.069	16,5	55	0,8	-	-	-	-	-	-
0,1	3.581	55,1	3.862	59,5	1.995	30,7	274	4,2	-	-
0,2	750	11,5	733	11,3	1.922	29,6	2.013	31,0	739	11,4
0,3	480	7,4	590	9,1	733	11,3	1.630	25,1	1.505	23,2
0,4	204	3,1	640	9,9	590	9,1	733	11,3	1.673	25,8
0,5	269	4,1	194	3,0	160	2,5	426	6,6	118	1,8
0,6	-	-	10	0,2	480	7,4	164	2,5	615	9,5
0,7	54	0,8	138	2,1	194	3,0	160	2,5	426	6,6
0,8	84	1,3	131	2,0	10	0,2	-	-	-	-
0,9	-	-	-	-	138	2,1	480	7,4	164	2,5
1	3	0,0	141	2,2	272	4,2	614	9,5	1.254	19,3

The expected damage is globally lower than that estimated for masonry: this result is obviously consistent with the observations after the Irpinia earthquake, but was also confirmed by the Marche-Umbria (1997) [Baratta et al. 1998] and the Pollino (1998) earthquakes. In Figure A.10 the number of collapsed buildings has been calculated by considering the sum of the buildings having $d \geq 0.9$. It has been considered that buildings with $d>0.8$ are almost collapsed and, in any case, have suffered such important partial failures of structural and non structural elements, that severe injuries and casualties can occur to the inhabitants.

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