EXPERT SYSTEM FOR DAMAGE ASSESSMENT OF BUILDINGS IN SEISMIC AREAS

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INTRODUCTION

The analysis of damage on buildings affected by an earthquake allow to trace back to the defects of the structural system and the imperfections of the constructive elements with reference to the best or worst behaviour in case of seismic action. As a matter of fact the tendency of buildings to be damaged, also defined as seismic vulnerability, is strictly connected with their geometric-constructive characteristics.

The damage appears as "effect" of the phenomenon that has its "cause" in the seismic action. Once the characteristics of the system are defined, it is possible to reconstruct the 'cause-effect' relation between seismic action and damage.

These relations can be obtained through survey of damage caused by recent earthquake. However this methodology reveals a series of problems. The various quantities applied must be expressed with indices that allow to synthesize complex and articulated scenarios exhaustively; although the damage is a quantity that can be directly assessed by description, it is difficult to measure, as its quantification should be representative for all aspects connected with it (physical, economic, functional, social, etc.). The level of the seismic action must be expressed by a parameter that is an index of the event's destructive capacity and in direct correlation with mechanical quantities (acceleration, velocity, energy, etc.). The vulnerability is an entity able to characterize the more or less accentuated predisposition of the structures to suffer damages independently from the intensity and direction of the seismic action.

In this work, subjects concerning seismic action and vulnerability shall not be dealt with, as they have already been investigated in previous works [see Grimaz S., 1992 - Cella F. et al., 1994 and 1995]; in the following the problem of damage quantification shall therefore be explored.

1 - DAMAGE QUANTIFICATION - THE STATE OF THE ART

A very diffuse version, often applied in Italy for damage quantification on buildings affected by a seismic event, consists in the *grade of damage* defined as the ratio between repair cost and cost for complete reconstruction. This indicator has the advantage to define damages by means of a continuous variable in the 0-1 interval, however it is dependent on characteristics of the building market and related technologies in a certain period and in some geographic area. It is therefore a rather subjective measure mainly aimed to calculate economic loss.

Another widely diffuse quantification often used in Italy is based on the *damage index*. This originates from the damage levels (null, light, medium, ...) typical for macro-seismic scales and thus discontinuous; therefore this index constitutes a continuous version, in the 0-1 range, of the damage levels. In this case, the proper methodological separation between damage and economical loss is obtained as in [Grimaz S., 1992]; however, the qualitative character of the damage status raises the problem of subjective interpretations.

To limit subjective interpretations, it has been tried to offer an alternative representation by highly detailed descriptions of the damage status. In the survey procedure proposed by the GNDT (National Group for Seismic Prevention), damages are evaluated and recorded by appropriate matrices that describe the damage status with the various extensions and damage levels, observed for every single floor and for every structural component [Angeletti P., 1984 - Angeletti P. et al., 1988]. The translation of all this in a damage index is obtained by the following weighted mean:

$$i.d. = \sum_{ij} S_i F_j D_{ij}$$

where D_{ij} is the damage index of the i-th component (vertical structures, horizontal structures, stairs, partition walls, ...) located on the j-th floor; S_i, and F_j are weighting coefficients that characterize the component and the floor.

Although it is very detailed in the type and quantity of information to be collected, the procedure actually used by the GNDT for the evaluation of the global index, still introduces weights that are partly related to economic considerations and not only to the physical damage state of buildings.

Even if this index is a suitable tool to assess the average cost of buildings repairing, there are some problems concerning the correlation studies between seismic action-vulnerability-damage. The vulnerability, in fact, characterizes the predisposition to the physical damage, so that, for the definition of the cause-effect relations, it is essential to refer to a damage quantification in terms of the overall structural functionality lack of the building.

The recent macroseismic scale proposed at European level (see e.g. EMS '92 scale [Grunthal G. ed., 1993]) defines a scale with 5 damage degrees associated to which there are predefined damage scenarios. The damage level is assigned by the comparison of the real scenario with those predefined in the scale.

The different way of damage quantification depends on the various application fields and on the targets of the analyses that are conducted.

In the seismic risk studies, damage forecast should permit the definition of a general state of the expected effects, under various points of view. The evaluation of an expected damage index should therefore permit to trace back to the characteristics of the physical damage of the building and to the conditions of repairability, usability and possible loss of human lives. In this way the index is also suitable for assessments connected with the planning and administration of post-earthquake emergencies.

The relation between earthquake, vulnerability and damage is often expressed through functions relating the level of seismic action and the vulnerability index to the damage index. Those functions can be derived from the damage data survey due to recent earthquakes. In the following a damage scale that tries to answer these requirements is given.

2 - SCALE OF SYNTHETIC DAMAGE JUDGEMENTS (GSD)

The aim of this scale is to provide a quantitative assessment of the damage suffered by a masonry building able to record information concerning peculiar characteristics of the damage scenario.

GRADE a	NEGLIGIBLE TO SLIGHT DAMAGE	**GSD i.d.= 0 - 10**
	loss of primary functionality: negligible; loss of secondary functionality: ranging from negligible to slight. *(hair-line cracks in few walls; fall of small pieces of plaster;* *fall of loose stones from upper parts of buildings in very few case only)* repairability: not necessary; usability: usable; victims probability for direct damages: negligible.	
GRADE b	MODERATE DAMAGE	**GSD i.d.= 10 - 30**
	loss of primary functionality: slight; loss of secondary functionality: moderate. *(medium cracks in many walls; fall of fairly large* *pieces of plaster; parts of chimneys fall down)* repairability: ranging from not necessary to complete; usability: usable with non structural work; victims probability for direct damages: negligible.	
GRADE c	HEAVY DAMAGE	**GSD i.d.= 30 - 50**
	loss of primary functionality: moderate; loss of secondary functionality: ranging from heavy to very heavy. *(large and extensive cracks in most walls;* *pantiles or slates slip off; chimneys are broken at the roof line;* *failure of individual non-structural elements)* repairability: complete; usability: usable with structural work; victims probability for direct damages: low.	
GRADE d	VERY HEAVY DAMAGE	**GSD i.d.= 50 - 70**
	loss of primary functionality: ranging from heavy to very heavy; loss of secondary functionality: ranging from very heavy to extremely heavy; *(very large cracks including relevant out of line and/or collapse* *of few main walls, low level cracks on other walls; partial collapse of roof)* repairability: ranging from partial to not suitable from structural point of view; usability: unusable; victims probability for direct damages: medium.	
GRADE e	HEAVIEST DAMAGE	**GSD i.d.= 70 - 90**
	loss of primary functionality: heaviest; loss of secondary functionality: total; *(serious failure in most walls; loss of horizontal structure* *and/or collapse of part of building)* repairability: impossible; usability: unusable; victims probability for direct damages: ranging from medium to high.	
GRADE f	DESTRUCTION	**GSD i.d.= 90 -100**
	loss of primary functionality: total; loss of secondary functionality: total; *(total collapse)* repairability: impossible; usability: unusable; victims probability for direct damages: high.	

Figure 1: Definition of GSD damage scale.

Table 1: Numerical range for each level of the GSD scale.

<table>
<tr><th></th><th colspan="2">0</th><th colspan="2">10</th><th colspan="2">20</th><th colspan="2">30</th><th colspan="2">40</th><th colspan="2">50</th><th colspan="2">60</th><th colspan="2">70</th><th colspan="2">80</th><th colspan="2">90</th><th>100</th></tr>
<tr><td>S.V.</td><td colspan="2">Ass_Danno</td><td colspan="2">CC</td><td colspan="4">CM</td><td colspan="4">LG</td><td colspan="2">CPL</td><td colspan="4">CPS</td><td colspan="2">CROLLO</td><td></td></tr>
<tr><td>S.O.</td><td colspan="2">Ass_Danno</td><td colspan="2">LL</td><td colspan="4">SMO</td><td colspan="4">SG</td><td colspan="2">CPL</td><td colspan="4">CPS</td><td colspan="2">CROLLO</td><td></td></tr>
<tr><td>COP.</td><td colspan="4">Ass_Danno</td><td colspan="4">SM</td><td colspan="4">SO</td><td colspan="4">CP</td><td colspan="4">CROLLO</td><td></td></tr>
<tr><td>Ripr.</td><td colspan="6">NN</td><td colspan="4">RT</td><td colspan="4">RP</td><td colspan="2">NO</td><td colspan="4">NF</td><td></td></tr>
<tr><td>Agib.</td><td colspan="2">AG</td><td colspan="4">ANS</td><td colspan="4">AS</td><td colspan="10">NA</td><td></td></tr>
<tr><td>p.V.i.</td><td colspan="8">Trasc.</td><td colspan="4">Bassa</td><td colspan="5">Media</td><td colspan="3">Alta</td><td></td></tr>
<tr><td>p.V.e.</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td colspan="5">Media</td><td></td><td></td><td></td><td></td></tr>
</table>

Damage Interpretations

(S.V.) Vertical structures

Ass_Danno	No damages
CC	Hair-line cracks
CM	Medium cracks
LG	Large cracks
CPL	Local partial collapse (< 50%)
CPS	Significative partial collapse (> 50%)
CROLLO	Total collapse

(S.O.) Horizontal structures

Ass_Danno	No damages
LL	Small loss of connections
SMO	Moderate loss of connections
SG	Heavy loss of connections
CPL	Local partial collapse (< 50%)
CPS	Significative partial collapse (>50%)
CROLLO	Total collapse

(COP.) Roof

Ass_Danno	No damages
SM	Damages on the roof-top
SO	Lack of structure connection
CP	Partial collapse
CROLLO	Total collapse

(Ripr.) Repairability

NN	Not necessary
RT	Restorable
RP	Partially restorable
NO	Not suitable
NF	Impossible

(Agib.) Usability

AG	Usable
ANS	Usable with non-structural work
AS	Usable with structural work
NA	Unusable

(p.V.i.) Victims probability INSIDE building

Trasc.	Negligible
Bassa	Low
Media	Medium
Alta	High

(p.V.e.) Victims probability OUTSIDE building

Media	Medium

A damage index is introduced with the aim to measure the loss of functionality from the pre-event to the post-event condition.

The functionality, in a structural sense, can be expressed in two components:

1. Primary functionality: structural elements as vertical and horizontal elements, roof, foundations;
2. Secondary functionality: non-structural elements as partition walls, projections, balconies, stairs, chimneys, plaster, pantiles or slates, installations.

The index tries to measure the loss of functionality (type and level of the loss) relating them to the level of the physical damage observed (damage with corresponding graduations).
It is strictly connected to the repairability (not in terms of economic convenience but practicability and structural opportunity) and usability (capacity of the building to resist to aftershocks). The fact that certain damage types are more or less correlated to possible loss of human lives is also considered. Obviously these last judgements are only a rough approximation, f.i. see the expert system proposed by [Pagnoni T. et al., (1989)] for more precise usability assessment. The complete definition of the GSD scale is given in figure 1.

In the grid (table 1) all possible effects of physical damage are individuated, this allows to stress the specific aspects that are related to different possible use of the scale (e.g. physical damage, possibility of repairing, usability judgement, possible loss of human lives).
In particular, the functionality loss in structural terms is decomposed in the analysis of the damage on vertical and horizontal structures and on the roof. A judgement on the level of repairability and usability of the building is added to this. Finally, the possible loss of human lives inside and outside the building is assessed.

All judgements placed on a 1 to 100 scale define a scenario that permits to assign a unique overall damage judgement. This result can be expressed either in numerical terms of damage index or in linguistic terms by a report that describes the entire damage scenario for a level of GSD scale. Obviously it is possible to consider the different aspects separately.
The damage assessment conducted by the GSD scale can be performed not only during a site survey, but also on the basis of photographic documentation [Casolo S. et el., 1993] or by the damage matrices of the GNDT vulnerability forms.

3 - DATASET

The expert system described in this work evaluates the damage index by means of the data collected on the buildings using the *form for exposure and vulnerability survey* [GNDT 1, 1994] developed by the National Project for Seismic Prevention (GNDT). Through this form a lot of surveys have been carried out in many different parts of Italy after events of different intensity.

The information used in this work can be found in the section 8 of the form: *extension and level of damage* (figure 2). In this section, the damage of the various constructive components (vertical structures, horizontal structures, stairs, partition walls) has been recorded for every floor of the building on the basis of six damage levels (null, light, medium, heavy, very heavy, total). The data are organized in 4 separate matrices and are expressed by letter codes increasing with the damage level from A to F. Every line of the matrix contains the damage survey observed on every floor; in case of homogeneous damage on various floors of the building only one row of the matrix is filled. The manual of the form [GNDT 2, 1994] gives detailed descriptions in order to guarantee a sufficient level of uniformity. The

Section 8 - EXTENSION AND LEVEL OF DAMAGE

Event date 301 | 0 | 6 | 0 | 5 | 7 | 6 |

1 earthquake 307 | 1 |
2 others

Damage level

Damage level	
No damage	**A**
Light damage	**B**
Medium damage	**C**
Heavy damage	**D**
Very heavy damage	**E**
Total damage	**F**

Installations damage: 1 yes, 2 no 388 | |

Extension of the damage

E ≤ 10 %	**0**
10 < E ≤ 20 %	**1**
20 < E ≤ 30 %	**2**
30 < E ≤ 40 %	**3**
40 < E ≤ 50 %	**4**
50 < E ≤ 60 %	**5**
60 < E ≤ 70 %	**6**
70 < E ≤ 80 %	**7**
80 < E ≤ 90 %	**8**
90 < E	**9**

Vertical Structures

	M	**E**	**L**	**N°**	**l**
308	E	3	D	2	1
312	E	6	E	2	1
316					
320					
324					

Horizzontal Structures

	M	**E**	**L**	**N°**	**l**
328	E	5	D	3	0
332	E	5	D	1	9
336					
340					
344					

Stairs

	M	**E**	**L**	**N°**	**l**
348	E	5	D	3	0
352	A	9	A	1	0
356					
360					
364					

Partition walls

	M	**E**	**L**	**N°**	**l**
368	E	3	D	2	0
372	E	6	E	2	0
376					
380					
384					

Figure 2: GNDT form for exposure and vulnerability survey (Section 8).

maximum damage level observed (**M**) and the most frequent damage (**L**) with its extension (**E**) are identified for every matrix line. For each floor the extension is expressed in 10 percentage intervals each coded from 0 to 9 [GNDT 1, 1994].

In this first version of the expert system only data referring to damage on vertical and horizontal structures and roofs have been used. The matrices containing the data for the stairs and the partition walls have not been considered as there are some uncertainties on the reliability of the surveys. In fact, the procedure can use all the four matrices or only the first two; in this application (the buildings of the old town of Venzone) only data regarding vertical and horizontal structures obtained from photographic documents have been used. On this basis only an extrapolation of the damage state inside the buildings is possible, as it is not always visible on the photographs.

In the pre-processing step, a control and correction procedure has been performed in order to check the consistency of the data form on the values of damage extension **E** related to the maximum damage **M** (see rules in the form manual [GNDT 2, 94]).

The data concerning the damage observed on the vertical and horizontal components thus elaborated, have then been stored in dBASE format and every record has been associated to a unique building code. This arrangement is in accordance with the organization of data used in the procedure of seismic vulnerability assessment described in [Cella F. et al., 95]. In that work, the data of the GNDT form have been placed in a Geographic Information System (GIS) (realized with s/w Arc/Info) and geo-coded on a map containing the buildings plan of the town under examination. The aim of this dataset is to maintain compatibility with the expert system previously developed for the vulnerability assessment. Starting with the availability of the alpha-numerical data (GNDT form) together with a geo-coded plan in graphic format (e.g. DXF), it is easy to evaluate both vulnerability indices [Cella F. et al., 95] and damage index inside the same GIS environment. It will therefore be easy to evaluate the variation of the correlation between vulnerability and damage indices when the parameters of the above mentioned procedures change (e.g. see [Meroni F. et al., 95]).

4 - THE EXPERT SYSTEM

The inferential module realized with the *Nexpert Object* shell (Neuron Data) evaluates the damage index applying the GSD scale directly on the GIS *Arc/Info* data-base (ESRI). Thus, Nexpert works as an Arc/Info server supplying the reasoning module that implements the assessments of the damage and vulnerability indices, otherwise hardly realized inside the GIS (see figure 3). The communication is effected by the data sharing (in dBASE format) of the vulnerability form related to the polygonal topology of Arc/Info and directly accessible by Nexpert.

The preliminary step consists in data retrieval process by the expert system. Following the philosophy of the knowledge bases built with Nexpert, every record extracted from the data-base is associated to an object linked to a proper class that has been already defined in the object-oriented knowledge base. The calculation methods for the parameters of the damage conditions for each structural components of the building are inherited from these classes.

At the end of the data acquisition phase, an inferential process for the assessment of the GSD damage index starts. The knowledge base implemented inside the expert system performs its assessment in two separated phases. In the first one a quantitative damage evaluation is performed according to the various interpretations of damage in the GSD scale. Only in a second phase, the obtained conclusions are put together in a unique value considered as overall damage index for the building.

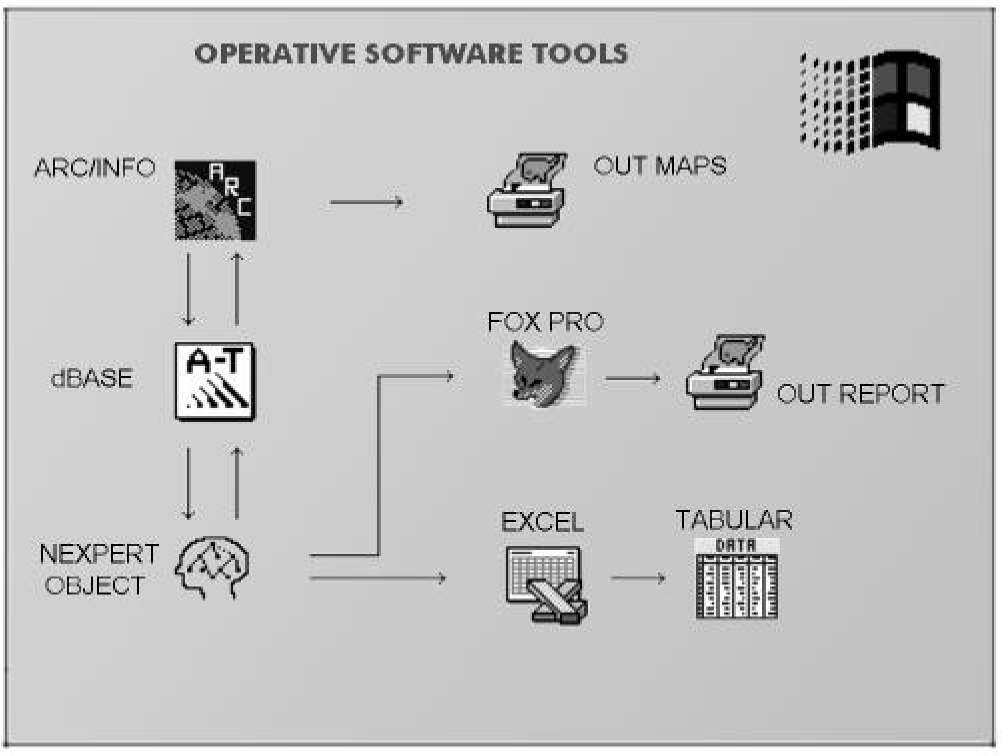

Figure 3: Adopted software tools for the expert system development.

4.1 - Rules for the assessment of the damage levels

The knowledge base assesses in sequence 6 set of rules in order to individuate, for every aspect of the building analysis, a precise damage level (for vertical and horizontal structures and the roofs) and a precise judgement (with regard to repairability, usability and loss of human lives). These levels and judgements (table 1) are directly obtained from the propositions of the GSD grades (figure 1). Further assessments have been added to those above indicated. The first concerns damage distribution with regard to the building floors, the second contains a preliminary index on which the calibration of the overall damage index will be based.

The objects representation of the damage matrices for the vertical and horizontal structures of the building, realized inside the working memory of Nexpert, individuates some significative features of the building by pattern-matching techniques. Further to the values of extension and damage level of every single floor, a maximum value **Max_M** (on all floors) for the vertical and horizontal structures is calculated from the object structure. Finally, for every floor, and distinctly for vertical and horizontal structures, a floor damage index **IDP** is calculated and its maximum value **Max_IDP** on the building is individuated.

The floor damage index **IDP** is defined as a combination of the maximum damage values M and the most frequent ones L (with its extension E); the following numerical values are assigned to the classes:

L [A, B, C, D, E, F]	-->	L [0, 0.2, 0.4, 0.6, 0.8, 1]
M [A, B, C, D, E, F]	-->	M [0, 0.2, 0,4. 0.6, 0.8, 1]

Unlike the floor damage GNDT index (see paragraph 1), defined as:

$$D_{ij} = EL + \frac{M\left(1 - E\right)}{3} \qquad (1)$$

the **IDP** index is defined in the following way:

$$\mathbf{IDP} = L + (bM - L)\frac{(1-E)}{(1-E_u)} \qquad (2)$$

where bM is the assigned damage value (proportional to the maximum damage M) when there is a uniform distribution on all damage levels with an extension E_u.

The **IDP** index (2) can be expressed assuming L as base level and adding a term depending on the difference between M and L with a calibration factor *b* (reducing the M value) and weighted by $\frac{(1-E)}{(1-E_u)}$. The last term represents a measure of the difference between the extension of the most frequent damage E and the extension E_u in case of uniform distribution on all damage classes.

Two particular cases are obtained:

* damage with monochromatic distribution --> L = M and E = 1 (100%), then **IDP** = L;

* uniform damage on all damage classes --> L = M and E = E_u, then **IDP** = bM.

Given the numerical values assumed for M, the extension corresponding to uniform distribution is E_u= 1/(5M+1), and (2) can be rewritten in function of the parameters M**,** L, E:

$$\mathbf{IDP} = L + (bM - L)\frac{(1 - E)(5M + 1)}{(5M)} \tag{3}$$

In this application $b = 2/3$, from experimental observations.

This **IDP** index gives a better measure of the damage level in case of non uniform damage distribution with respect to the one obtained with (1). The **IDP** index holds a trace of a complex damage description on every single floor, distinctly for vertical and horizontal structures. A same **IDP** value is also calculated for the roof.

4.1.1 - First level rules

The rules' format are synthesized in tables 2a, 2b, 2c, 2d, 2e, 2f, respectively for the damage assessment of the vertical and horizontal structures, of the roof and for the judgements on repairability, usability and loss of human lives. Every table is subdivided vertically in two main parts: in the first there are assessments on **Max_M** value, in the second those on the floor damage index **IDP**. Every line of the table contains the rules for the damage level assignment (tables 2a, 2b, 2c) or judgement (tables 2d, 2e, 2f). Details of the table 2a for the damage assessment on the vertical structures are described in the following.

The damage levels on the vertical structures that can be identified on the GSD scale are:

1. total collapse	------->	CROLLO
2. significative partial collapse (> 50% of the structure)	------->	CPS
3. local partial collapse (< 50% of the structure)	------->	CPL
4. large cracks	------->	LG
5. medium cracks	------->	CM
6. hair-line cracks	------->	CC
7. no damages	------->	Ass_Danno

and the rules for the assessment are:

1. CROLLO - **Max_M** = F (total damage) on the ground floor;
floor damage index **IDP** ≥ 0.9 on most of the floors.
2. CPS - **Max_M** = F or E (total or very heavy damage) on any floor;
floor damage index $0.7 \leq$ **IDP** < 0.9 on most of the floors.
3. CPL - **Max_M** = F (total damage) on any floor;
floor damage index $0.6 \leq$ **IDP** < 0.7 on few floors;
or
Max_M = E (very heavy damage) on any floor;
floor damage index $0.6 \leq$ **IDP** < 0.7 on most of the floors.
4. LG - **Max_M** = E or D (very heavy or heavy damage) on any floor;
floor damage index $0.4 \leq$ **IDP** < 0.6 on at least half of the floors.
5. CM - **Max_M** = D or C (heavy or medium damage) on any floor;
floor damage index $0.2 \leq$ **IDP** < 0.4 on at least half of the floors.
6. CC - **Max_M** = C or B (medium or light damage) on any floor;
floor damage index $0 <$ **IDP** < 0.2 on any floor.
7. Ass_Danno - **Max_M** = A (null) all over the buildings;
floor damage index **IDP** $= 0$ all over the buildings.

Table 2a: Vertical structures rules (evaluated on S.V. matrix)

Levels	Max_M	Floors	IDP	Floors
CROLLO	F	on the ground floor	$IDP \geq 0.9$	on most of the floors
CPS	F or E	on any floor	$0.7 \leq IDP < 0.9$	on most of the floors
CPL	F	on any floor	$0.6 \leq IDP < 0.7$	on few floors
	E	on any floor	$0.6 \leq IDP < 0.7$	on most of the floors
LG	E or D	on any floor	$0.4 \leq IDP < 0.6$	on at least half of the floors
CM	D or C	on any floor	$0.2 \leq IDP < 0.4$	on at least half of the floors
CC	C or B	on any floor	$0 < IDP < 0.2$	on any floor
Ass_Danno	A	all over the building	$IDP = 0$	all over the building

Table 2b: Horizontal structures rules (evaluated on S.O. matrix)

Levels	Max_M	Floors	IDP	Floors
CROLLO	F	on the ground floor	$IDP \geq 0.9$	on most of the floors
CPS	F or E	on any floor	$0.7 \leq IDP < 0.9$	on most of the floors
CPL	F	on any floor	$0.6 \leq IDP < 0.7$	on few floors
	E	on any floor	$0.6 \leq IDP < 0.7$	on most of the floors
SG	E or D	on any floor	$0.4 \leq IDP < 0.6$	on more than one floor
SMO	D or C	on any floor	$0.2 \leq IDP < 0.4$	on at least half of the floors
LL	C or B	on any floor	$0 < IDP < 0.2$	on any floor
Ass_Danno	A	all over the building	$IDP = 0$	all over the building

Table 2c: Roof rules (evaluated on S.O. matrix)

Levels	M	Floors	IDP	Floors
CROLLO	F	on the last floor	$IDP \geq 0.8$	on the last floor
CP	F or E	on the last floor	$0.6 \leq IDP < 0.8$	on the last floor
SO	D or C	on the last floor	$0.4 \leq IDP < 0.6$	on the last floor
SM	C or B	on the last floor	$0.2 \leq IDP < 0.4$	on the last floor
Ass_Danno	A	on the last floor	$IDP < 0.2$	on the last floor

Table 2d: Repairability rules (evaluated on S.V. matrix)

Levels	Max_M	Floors	IDP	Floors
NF	F	on any floor	$IDP \geq 0.8$	on most of the floors
NO	F or E	on any floor	$0.7 \leq IDP < 0.8$	on most of the floors
RP	F or E	on any floor	$0.5 \leq IDP < 0.7$	on few floors
RT	D or C	on any floor	$0.3 \leq IDP < 0.5$	on any floor
NN	B or A	on any floor	$IDP < 0.3$	all over the building

If previous level = RT or NN -----> Evaluate the above rule on S.O. matrix.

RT	any classes	on any floor	$IDP \geq 0.4$	on any floor

Table 2e: Usability rules (evaluated on S.V. matrix)

Levels	M	Floors	IDP	Floors
NA	any classes	on any floor	$IDP \geq 0.5$	on any floor
AS	F or E	only on one floor	$0.3 \leq IDP < 0.5$	on any floor
	D or C	on any floor	$0.3 \leq IDP < 0.5$	on any floor
ANS	C	on any floor	$0.1 \leq IDP < 0.3$	on any floor
AG	B or A	on any floor	$IDP < 0.1$	on any floor

If previous rules = ANS or AG -----> Evaluate roof useability on S.O. matrix.

NA	F or E	on the last floor	$IDP \geq 0.65$	on the last floor
AS	D or C	on the last floor	$0.4 \leq IDP < 0.65$	on the last floor
ANS	C or B	on the last floor	$0.1 \leq IDP < 0.4$	on the last floor
AG	B or A	on the last floor	$IDP < 0.1$	on the last floor

------> Take the worst result.

Table 2f: Victims probability (inside building) (evaluated on S.O. matrix)

Levels	M	Floors	IDP	Floors
Alta	F	on any floor	$IDP \geq 0.8$	on most of the floors
Media	F	on any floor	$0.7 \leq IDP < 0.8$	on few floors
	F	on any floor	$0.6 \leq IDP < 0.7$	on at least half of the floors
Bassa	E or D	on any floor	$0.4 \leq IDP < 0.6$	on any floor
Trasc.	C or B or A	on any floor	$IDP < 0.4$	on any floor

Victims probability (outside building) (evaluated on S.V. matrix)

Media	F	on any floor	$IDP \geq 0.8$	on top floors

The rules on tables 2b, 2c, 2d, 2e, 2f for the damage assessment of horizontal structures, roofs and for the judgements on repairability, usability and possible loss of human lives are to be interpreted in the same way. Note that in case of repairability, the damage on the horizontal structures is considered only if the damage on the vertical structures has an NN value (not necessary). In the same way, for the assessment of the usability of the building, the damage of the roof is considered only if the first set of rules on the vertical structures results to be ANS or AG (usable with non-structural work - usable). Finally, the probability of loss of human lives is considered distinctly inside and outside the building. In the first case, the damage on the horizontal structures is taken into consideration; in the second case only collapses of bearing walls on the high floors of the building are significant.

The quantities used inside the knowledge base (on most, at least half, a few ...) are codified by other rules that assess these entities according to the height of the building (floors number).

4.1.2 - Second level rules

If the previous set of rules is not able to assign a unique damage level, a second set of rules starts. With these rules the building is assigned not to a single class but at two contiguous

classes. One more parameter is evaluated on the building: the average floor index **Mean_IDP**, obtained from the average of **IDP** values weighted using the floor volume.
As the first step a damage level is set, based on the average index **Mean_IDP** and using the same numerical ranges of tables 2 (values in the 4th column of the table). A check is done to see if **Max_M** leads to the same grade of damage. As the third step the **IDP** indices are used in order to identify if the uncertainty is in the upper or lower level; to this purpose the **IDP** indices are compared with ranges larger then the previous one; in a first time the range is enlarged in such a way to consider the current class and the upper one, in a second time the range is enlarged toward the inferior class. Then the **IDP** values are compared with these new ranges and if only one situation is established a *double grade* is assigned. For a better comprehension, two cases of second level rules for damage on vertical structures are given below:

CROLLO/CPS - **Max_M** = F (total damage) on the ground floor;
average floor damage index $\mathbf{Mean\_IDP} \geq 0.9$;
floor damage index $\mathbf{IDP} \geq 0.7$ on most of the floors.

CM/LG - **Max_M** = D or C (heavy or medium damage) on any floor;
average floor damage index $0.2 \leq \mathbf{Mean\_IDP} < 0.4$;
floor damage index $0.2 \leq \mathbf{IDP} < 0.6$ on at least half of the floors.

The result of this set of rules holds memory of the range in which **Mean_IDP** is belonging; following this procedure two types of *double grade* can be assigned (e.g. CROLLO/CPS vs. CPS/CROLLO). Anyhow, the numerical score (as in table 1) used for the assessment of the overall damage index and associated to these results are the same in both cases (the new numerical scores are obtained from interpolation between the scores associated to every single level of table 1 - e.g. CPS/CROLLO = 80 - 95).

4.1.3 - Third level rules

If even the second level rules cannot determine a *double grade* univocally (due to non-realization of the conditions on **Mean_IDP, Max_M** and **IDP** at the same time or the activation of two rules at the same time), a set of rules with univocal result has been introduced. It was decided to understand this event as a presence of a very *scattered* damage type on the building structure. In this case, a final damage index of the building **IDP_Ris** is assessed, using the relation (3) where the values for L and M are substituted by **Mean_IDP** and **Max_M**:

$$\mathbf{IDP\_Ris} = \mathbf{Mean\_IDP} + \left(b\mathbf{Max\_M} - \mathbf{Mean\_IDP}\right)\frac{\left(1-0.85\right)\left(5\mathbf{Max\_M}+1\right)}{\left(5\mathbf{Max\_M}\right)} \tag{4}$$

and where the extension E of the damage **Mean_IDP** on the building is considered equal to 85%.

To establish the final level of damage the values of **IDP_Ris** is compared with the ranges indicated in tables 2. As a result the assessment will be:

CROLLO - when the index is: $\mathbf{IDP\_Ris} \geq 0.9$;
CPS - when the index is: $0.7 \leq \mathbf{IDP\_Ris} < 0.9$;
CPL - when the index is: $0.6 \leq \mathbf{IDP\_Ris} < 0.7$;
LG - when the index is: $0.4 \leq \mathbf{IDP\_Ris} < 0.6$;
CM - when the index is: $0.2 \leq \mathbf{IDP\_Ris} < 0.4$;
CC - when the index is: $0 < \mathbf{IDP\_Ris} < 0.2$.

An information about **Max_M** is added to the level of damage obtained from the rule (e.g. LG-F); this result holds memory for building with very *scattered* damage situation. For instance if $0.4 \leq \textbf{IDP\_Ris} < 0.6$ the LG class of damage is obtained and **Max_M** = F is added to the result (collapse it is not included in the damage class LG - large cracks). In other words the result must be read as the presence of a small 'spot' of elevated damage in a building with general damage of inferior level.
This type of result found on vertical structures will lead to a particular assessment process for the overall damage index of the building (see in paragraph 4.2).

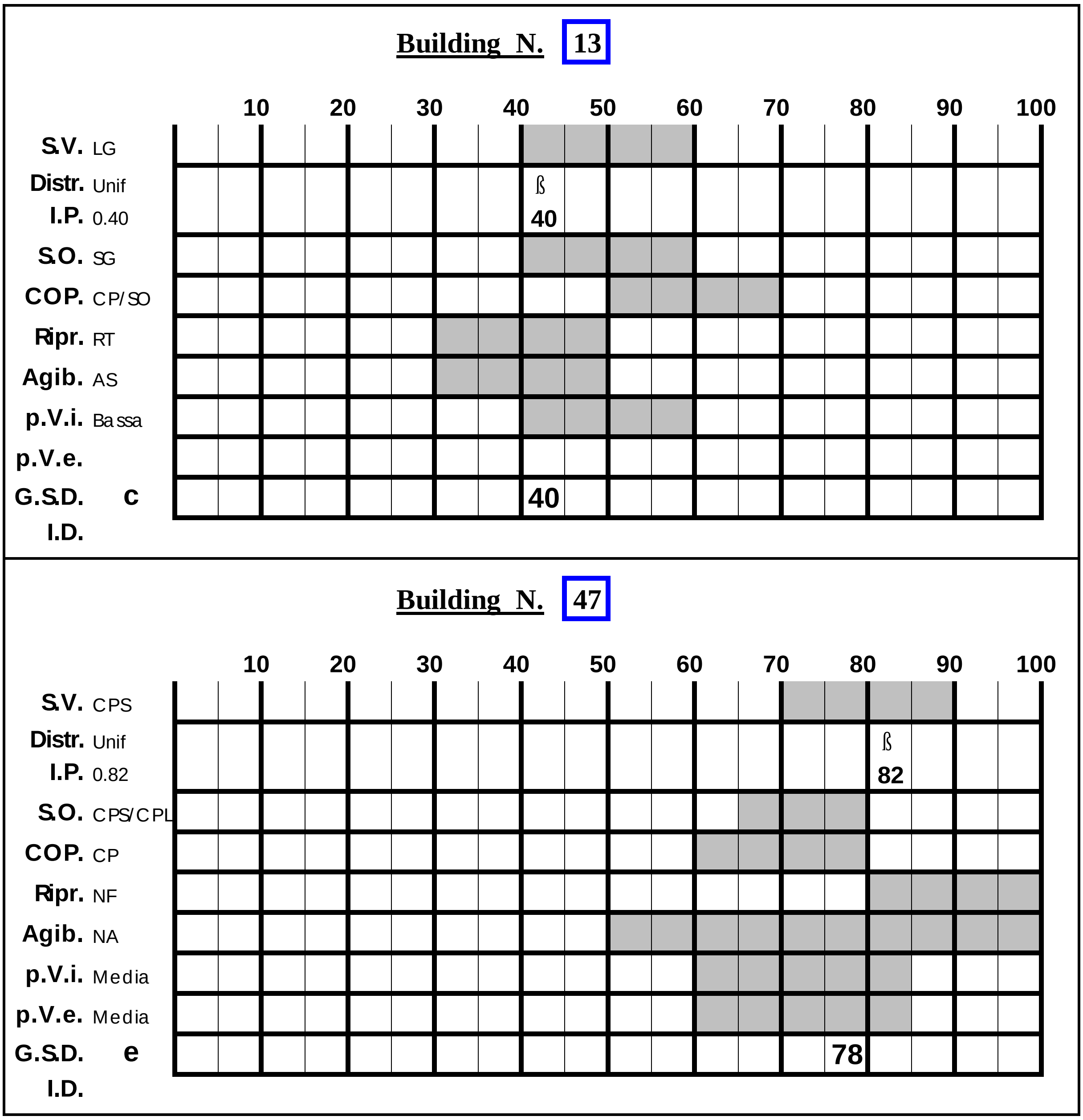

Figure 4: Expert system results - tabular form with scores (building n.13-4a; building n.47-4b).

4.2 - Rules for the assessment of the overall damage index

The second phase of the inferential process evaluates the overall index using the conclusions obtained by the 6 different damage interpretations of the GSD scale. Representing the results obtained with the rules above explained in a graphical way, figures 4a and 4b show the results obtained for building n.13 and 47 on bar graphs. Every row of the graph represents all the damage interpretations of the GSD scale. The meaning of the nine rows is:

1. damage on vertical structures (**S.V.**)
2. damage distribution on the building (with regard to the building's height) (**Distr.**)
3. average floor damage index **Mean_IDP** (evaluated on the vertical structures) (**I.P.**)
4. damage on horizontal structures (**S.O.**)
5. damage on the roof (**COP.**)
6. repairability (**Ripr.**)
7. usability (**Agib.**)
8. probability of victims inside building (**p.V.i.**)
9. probability of victims outside building (**p.V.e.**).

The position and the length of every bar describes the expert system conclusion in a graphical shape, where the numerical scores are those indicated in table 1 (paragraph 2). It is obvious that the result of the overall damage GSD index must arise from a kind of combination of the horizontal bars. This final index will be obtained on the basis of such numerical scores, using the following set of rules.

It is assumed that the most significative factor is the evaluation of the damage on the bearing walls (**S.V.**). Thus, the range of **S.V.** interpretation will be associated to the overall damage GSD index. In fact, if all approximations in the damage index assessment are considered, it is reasonable to evaluate the overall index within a range of variability. The starting point for the final index computation is the **I.P.** value (level 3 of the graph). For the most significative meaning of the damage on the vertical structure, whenever this value is external to the **S.V.** range, **I.P.** will be brought to the nearest extreme limit of the **S.V.** range. In the following step, the **I.P.** value will be modified on the basis of the indications for **S.O.**, **COP.** and **Ripr.** (levels 4, 5 and 6); these damage interpretations work as *attractors* in one of the two directions in respect to the **I.P.** starting value. Briefly, the procedure is the following:

- Starting value for the final index --> **I.P.** (with **S.V.** range);
- **I.P.** check on **S.V.** range; if external to **S.V.** range, move inside that range;
- Application of the *attractors* for **S.O.**, **COP.** and **Ripr.** with the following rules:

  if **Max_S.O.** (**COP.**, **Ripr.**) > **Max_S.V.** *and* **Min_S.O.** (**COP.**, **Ripr.**) > **Min_S.V.**
  then ---------------> Increase the **I.P.** value

  if **Min_S.O.** (**COP.**, **Ripr.**) < **Min_S.V.** *and* **Max_S.O.** (**COP.**, **Ripr.**) < **Max_S.V.**
  then ---------------> Decrease the **I.P.** value

  if **Max_S.O.** (**COP.**, **Ripr.**) ≥ **Max_S.V.** *and* **Min_S.O.** (**COP.**, **Ripr.**) ≤ **Min_S.V.**
  then ---------------> Confirm the **I.P.** value

  if **Max_S.O.** (**COP.**, **Ripr.**) ≤ **Max_S.V.** *and* **Min_S.O.** (**COP.**, **Ripr.**) ≥ **Min_S.V.**
  then ---------------> Confirm the **I.P.** value

where **Max_S.O**. and **Min_S.O.** (**COP., Ripr.**), respectively, are the higher and lower extreme limits of the **S.O.** range (**COP., Ripr.**);

- Weights of *attractors* : **S.O.** = 30% (of the **S.V.** range),
  COP. = 30% (of the **S.V.** range),
  Ripr. = 40% (of the **S.V.** range);

  Note: When one of the above *attractors* confirms of the **I.P.** value, the effect of the remaining *attractors* is reduced by 25% of their total weight.

- Final check of **GSD_ID** index on the **S.V.** range; if external move to the nearest extreme limit of the **S.V.** interval.

The above procedure cannot be applied when a very *scattered* damage is present (activation of the third level rules). There are two possible cases: the first procedure is applied when the damage for vertical structures is scattered with a result such as LG-F. The second procedure is applied when **S.V.** gives a precise damage level and **S.O.**, **COP.** or **Ripr.** contain scattered results.

In the first case it seems sufficient to calculate an average value between the maximum damage of the building **Max_M** and the average **I.P.** value, reproducing the assignment of the damage index values by expert operators. The following weighted average value is used:

$$\mathbf{GSD\_ID} = [(\mathbf{Max\_M} - \mathbf{I.P.})a + \mathbf{I.P.}] \qquad (5)$$

where: $a = 0.2$ if $\mathbf{Max\_M} \le D$,

$a = 0.3$ if $\mathbf{Max\_M} > D$.

The obtained result for **GSD_ID** will be used as overall damage index for the building.

The second procedure applied in presence of scattered damage on **S.O.**, **COP.** and **Ripr.**, allows to evaluate the direction of the *attractors* using an average value on the central point of the interval associated with these results. The relation (5) is used with **I.P.** index replaced by the average point of the range associated with this damage assessment (e.g. **S.O.** = SG-F ---> **Max_M** = F and average point of SG range is (60+40)/2=50). The obtained value is compared with the **S.V.** range for the possible application of the *attractor* in one of the two directions.

The final result of the GSD damage index is composed by a value from 0 to 100, with an associated range of variation relative to the damage on the vertical structures **S.V.** This final value **GSD_ID** is represented at the bottom of the graph (figures 4) containing the damage description according to the 6 classifications of the GSD scale.

5 - CASE OF THE TOWN OF VENZONE

The study area is the centre of Venzone town located north of the city of Udine (Friuli, Italy) at the head of the Tagliamento valley, with the Carniche foothills behind. The site began its economic growth around the year 1200 with the growth of trade with other European countries. The town centre composed of masonry buildings of two to four floors is surrounded by city walls. On the site one can identify, from the year 1000, at least seven

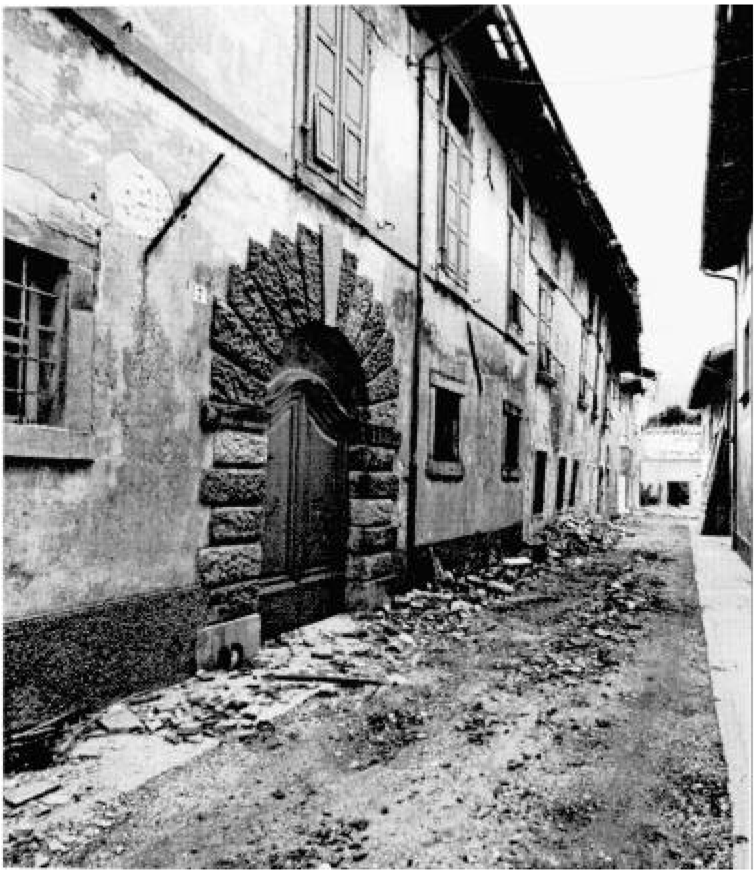

Figure 5a: Venzone town - Building n. 13.

Figure 5b: Venzone town - Building n. 47.

seismic events with an intensity greater than VII. The recent events of May 1976, and again in September of the same year with an intensity of IX on the Mercalli scale, damaged almost all the buildings and destroyed some of them. The documents and images available in the municipality archives describe the state of the buildings before the events and the damage caused by the shocks of May and September. The documentation was rather complete for 98 buildings on which the investigations are performed.

From this material the GNDT vulnerability forms and the damage matrices of figure 2 have been filled in; on these data the expert system performs the GSD damage index assessments. Unfortunately, the procedure applied for the compilation has introduced further elements of uncertainty inside the evaluation process. In fact, the on site damage observation performed by a post-earthquake survey would have improved the quality and the precision of the data avoiding the lack of information due to the partial visibility of the buildings in some photographs (e.g. the damage on the horizontal structures that cannot be surveyed by the photographs taken from outside of the building).

Now the results obtained by the application of the expert system on two buildings (figures 5a and 5b) of a damage class placed almost at the GSD scale limits will be analyzed in detail: building 13 presents relatively low damage and building 47 presents a large damage; the related data are shown in tables 3a and 3b. The output of the expert system is provided either in tabular form (figures 4) or in natural language report (figures 6). These output forms have been codified outside the expert system shell (Nexpert Object), using the communication protocol DDE (Dynamic Data Exchange) of Ms-Windows, respectively with Microsoft Excel and FoxPro.

Every decision obtained by the expert system is provided on distinct levels (figures 4), where the width of the horizontal bars is coherent with the values of the GSD scale (see table 1). The superimposition of these bars gives an overview on how the overall damage index has been obtained (procedure of paragraph 4.2). This final value is to be found in the last line at the bottom of the table and represents the physical damage of the building. Adding the description of the damage in natural language to the table, even a non expert user can understand the results of the different aspects examined by the GSD scale. Therefore the comparison of the results with the photographic images of the building becomes immediate. For example, for building n° 13 it is possible to see from figure 4a how the final GSD index is obtained. The starting value of the damage index is **I.P.** = 40. Its range is 40 - 60, associated to **S.V.** The effect of the *attractors* **S.O.**, **COP.** and **Ripr.** would lead to decrease the starting value (**S.O.** -> confirm, **COP.** -> increase and **Ripr.** -> decrease). The final GSD index, however, will remain within the lower bound of the **S.V.** range (40), as it is not possible to go outside. The final result therefore corresponds to the ***c*** grade (Heavy Damage).

Table 3: Basic data for vertical and horizontal structures (building n.13-3a; building n.47-3b)

Building N. 13

Vertical structures

	M	E	L	N°	l
308	D	4	C	1	2
312	D	4	C	2	2
316	D	4	C	3	2
320					
324					

Horizzontal structures

	M	E	L	N°	l
328	D	4	C	1	0
332	D	4	C	2	0
336	E	4	D	9	9
340					
344					

Building N. 47

Vertical structures

	M	E	L	N°	l
348	F	4	E	1	2
352	F	6	F	2	5
356	F	6	F	3	5
360	F	6	F	4	5
364					

Horizzontal structures

	M	E	L	N°	l
368	E	5	E	1	0
372	F	3	E	2	2
376	F	4	F	3	4
380	F	4	F	9	4
384					

Building N. 13	
VERTICAL STRUCTURES	Appearance of large cracks on vertical structures.
ROOF	Some small collapse of the coverage with serious lacks of structure connection.
DAMAGE DISTRIBUTION	Uniform distribution of the damage on all floors.
HORIZONTAL STRUCTURES	Appearance of heavy loss of connections to the horizontal structures.
REPAIRABILITY	The building is wholly repairable.
USABILITY	The building is usable with structural works.
VICTIMS PROBABILITY INSIDE BUILDING	Low probability of victims inside the building.
VICTIMS PROBABILITY OUTSIDE BUILDING	Victims probability outside the building is not valuable.
Building N. 47	
VERTICAL STRUCTURES	Appearance of significative partial collapse or serious failure on more than half of vertical structures.
ROOF	Appearance of partial collapse or serious failure of parts of the coverage.
DAMAGE DISTRIBUTION	Uniform distribution of the damage on all floors.
HORIZONTAL STRUCTURES	Collapse of about 50 % of the horizontal structures.
REPAIRABILITY	The building it is not repairable.
USABILITY	The building is unusable.
VICTIMS PROBABILITY INSIDE BUILDING	Medium probability of victims inside the building.
VICTIMS PROBABILITY OUTSIDE BUILDING	Medium probability of victims outside the building.

Figure 6: Expert system results - natural language report (building n.13 -6a; building n.47 -6b).

From the analysis of building n° 47 other considerations can be made. From the figure 5b the building appears as extremely damaged with total collapse of the roof. Nevertheless from the output of the expert system (figures 4b and 6b) the damage seems to be lower giving a partial collapse of the roof (**COP.** = CP). The ambiguous result comes from the partial view of the building n° 47 in the picture that doesn't allows to establish the exact entity of the damage, while the matrix used by the expert system (table 3b) is compiled with all

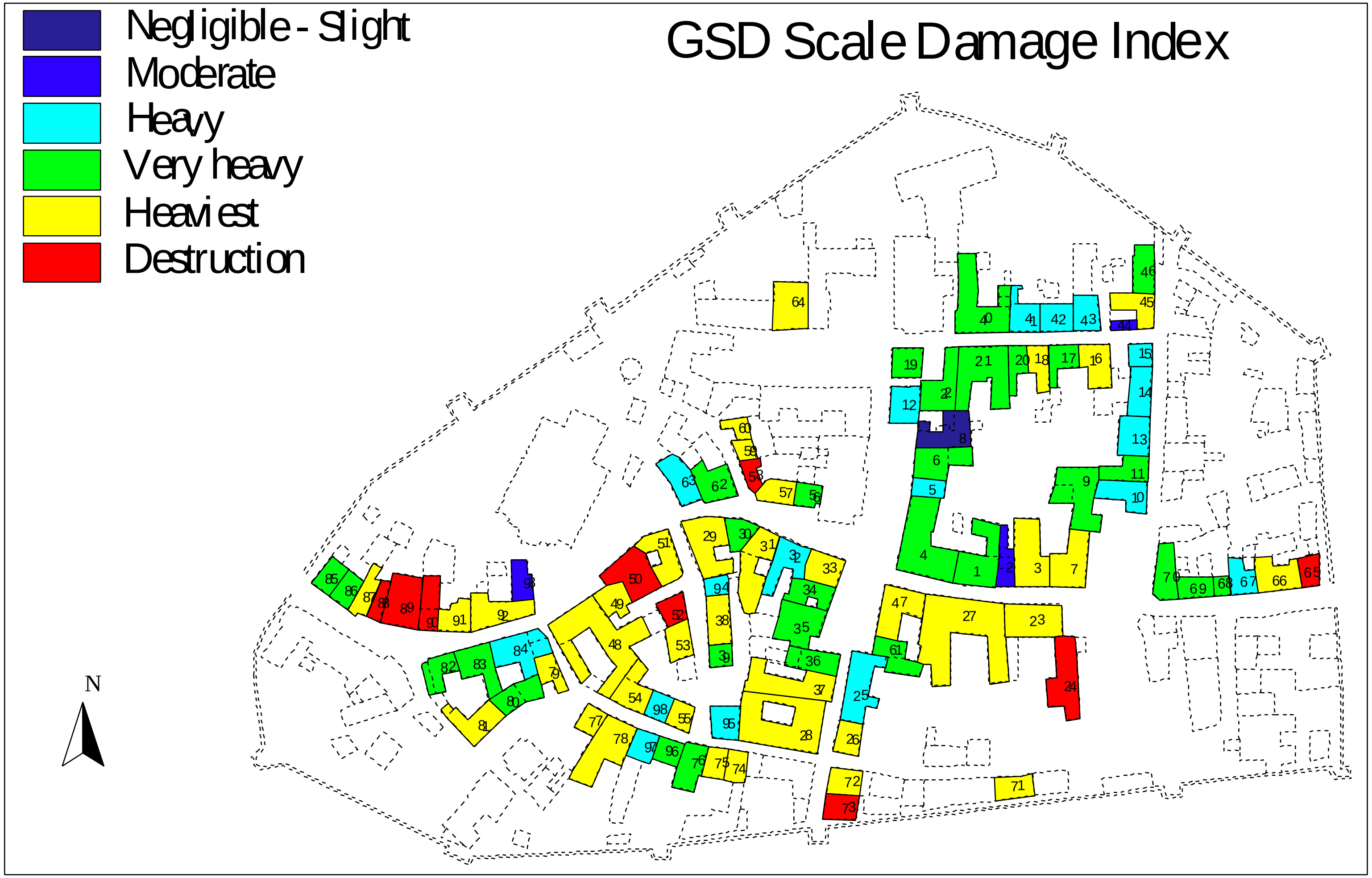

Figure 7: GSD_ID index for Venzone town.

information available on the building. This shows the efficiency of the expert system in damage assessment process, eliminating any subjective assumption of the human operator in the pictures analyses.

A geocoded result can be also obtained through the GIS in form of thematic maps in which the GSD damage index is indicated according to 6 scale grades (figure 7).

It is also possible to produce maps similar to the preceding one, in which not only the damage on the buildings is represented but also the repairability, the usability and the possible loss of human lives inside and outside the buildings. These risk maps are a very useful in post-earthquake interventions.

6 - CONCLUSIONS

The damage index map can be compared with the vulnerability map produced with an expert system developed in a previous work [Cella F. et al., 1994] in the same GIS environment. From this analysis it is possible to investigate the correlation between vulnerability and damage index for a given level of seismic action [Meroni F. et al., 95].

The developed software tool, codifying the GSD damage scale, allows to quantify the damage level of buildings affected by an earthquake and permits to trace back the peculiar characteristics of the damage scenario. In this way it is possible to describe the physical damage on the building, the repairability, the usability and the possible loss of human lives. Using such damage index in the study of correlation between seismic action-vulnerability-damage, permits to produce, for future events, many different scenarios, one for each damage interpretation of the GSD scale.

Actually, the procedure can be applied using the damage matrices of the GNDT form and allows to formulate automatically and objectively a synthetic judgement of the damage. It can be applied on the whole database containing the GNDT forms for towns in different parts of Italy. When h/w and s/w characteristics will be available on portable computers this tool could be implemented to permit an elaboration of a damage report and to furnish the synthetic damage judgement directly from on-site observations. This possibility, considering the coherence with the damage evaluation adopted in the EMS scale, could make this instrument useful also for damage assessment in macroseismic studies.

REFERENCES

Angeletti P. (1984). *Un modello per la valutazione dei costi di riparazione e adeguamento sulla base dei censimenti di danno e vulnerabilità.* Atti seminario internazionale "Vulnerabilità ai terremoti e metodi per la riduzione del rischio sismico", Noto.

Angeletti P., Bellina A., Guagenti E., Moretti A., Petrini V. (1988). *Un modello per la valutazione dei costi di riparazione e adeguamento sulla base dei censimenti di danno e vulnerabilità.* Proceedings of the 9th World Conference on Earthquake Engineering, Tokyo-Kyoto.

Casolo S., Grimaz S., Petrini V. (1993). *Scala dei Giudizi sintetici di stima del danno sismico. Scala G.S.D.e.m. 93.* Rapporto interno - Quaderni del laboratorio di Sismologia - Dipartimento di Georisorse e Territorio, Università degli Studi di Udine.

Cella F., Grimaz S., Meroni F., Petrini V., Tomasoni R., Zonno G. (1994). *A case study for seismic vulnerability assessment using GIS connected to Expert System.* Proceedings 9th Arc/Info European conference, 5-7 October 1994, Paris, France.

Cella F., Grimaz S., Meroni F., Petrini V., Tomasoni R., Zonno G. (1995). *An application on Geographic Information Systems connected to Expert System.* Cahiers du Centre Européen de Géodynamique et de Séismologie, Volume 9. Walfardange - Luxembourg, November 1993.

Grimaz S., (1992). *Relazione scientifica finale sull'attività svolta nell'anno 1992.* Gruppo di ricerca finalizzata di protezione civile nel settore del rischio sismico - Regione Autonoma Friuli Venezia Giulia - Università degli Studi di Udine

GNDT 1, (1994). *Scheda di esposizione e vulnerabilità di primo livello e di rilevamento danni.* Gruppo Nazionale per la Difesa dai Terremoti - Roma.

GNDT 2, (1994). *Istruzioni per la compilazione della scheda di rilevamento di esposizione e vulnerabilità sismica degli edifici in muratura.* Gruppo Nazionale per la Difesa dai Terremoti - Roma.

Grunthal G. Ed. (1993). *European Macroseismic Scale 1992.* Cahiers du Centre Européen de Géodynamique et de Séismologie, Volume 7, Luxembourg.

Meroni F., Tomasoni R., Grimaz S., Petrini V., Zonno G., Cella F. (1995). *Assessment of seismic effective vulnerability using Arc/Info connected to Nexpert.* Proceedings of the 5th International Conference on Seismic Zonation - Nice - France, October 17th - 19th, 1995, vol. I, pp. 68-75.

Pagnoni T., Tazir Z.H., Gavarini C. (1989). *AMADEUS a KBS for the assessment of earthquake damaged buildings.* Report of IABSE Colloquium on Expert Systems in Civil Engineering - Bergamo - Italy, 1989, vol. 58, pp. 141-150.