Seismic vulnerability of historic centres: identification of damage mechanisms occurred in Arsita (TE) after L'Aquila earthquake

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15 WCEE
LISBOA 2012

SUMMARY:
In the current paper a survey activity performed on the historical centre of Arsita, a town hit by L'Aquila earthquake, is presented. This research activity, carried out by filling *ad hoc* survey forms related to different disciplinary approaches, has been conducted by a scientific team headed by ENEA with the cooperation of the Universities of Naples, Chieti-Pescara and Ferrara. The work targeted on the following topics: a) to perform in situ surveys, b) to assess natural and anthropogenic hazards, c) to evaluate construction vulnerability and risk, d) to individuate construction damage, e) to compare detected damage with predicted one.
The investigation has permitted to gather general information and useful elements about the town in order to prepare the Post- Earthquake Reconstruction Plan for the Arsita Municipality (through in situ and laboratory work), which is now in progress and will be terminated within the end of the next summer.

Keywords: L'Aquila earthquake, historic centres, masonry structures, vulnerability assessment methods, reconstruction plan

1. INTRODUCTIONARY REMARKS

Arsita (Fig. 1.1) is a town of 892 inhabitants, located in the district of Teramo (Abruzzo Region), near the Gran Sasso Massif (Fig. 1.2). The small and nice historic centre presents very inhomogeneous built up with regard to earthquake damages, vulnerability, past interventions, maintenance and marks of past seismic events. The ancient nucleus consisted in a fortified construction (a masonry tower now in ruins), due to its strategic importance in the territory, giving to the place the present wonderful position in the landscape. Furthermore, the historic centre enshrines notable palaces and churches.
About two years after the April 6th, 2009 L'Aquila (Italy) seismic event, a scientific team set up by ENEA (*Italian National Agency for New Technologies, Energy and Sustainable Economic Development*), with the Universities of Pescara-Chieti "G. D'Annunzio", Naples "Federico II" and Ferrara, visited the Municipality of Arsita to show the resources for training and demonstration activities in the framework of the Master in "Bio-sustainable Architecture" of University of Bologna.
Although the Intensity level (VI MCS) of L'Aquila earthquake may be considered moderate, the combination of several factors (mainly high potential vulnerability, particular topographic and soil conditions, that should be accurately deepened in the framework of the future work) led to a non

negligible widespread damage. In addition, the Arsita Technical Office defined also the building aggregates (depending on their structural continuity) to be either repaired or rehabilitated.
Thus, the investigation of the historical centre was focused on the effectiveness of a multidisciplinary approach based on the simultaneous application of Remote Sensing techniques, GIS (Geographical Information System) tools, DGPS and Laser Scanner surveys, together with some quick and more refined procedures for vulnerability evaluation, namely Famive, GNDT, a vulnerability assessment forms purposely conceived for masonry aggregates and MEDEA.
The next phase of the activity, to be finished in the summer 2012, will consist in the detailed preparation of the Post-Earthquake Reconstruction Plan for the Arsita Municipality (through in situ and laboratory work), which is going to be entrusted to ENEA (as team leader), with the support of the above mentioned universities. This phase has been started after a specific agreement among ENEA, the Universities and the Arsita Municipalilty.

Figure 1.1. Arsita plan view

(a) (b)

Figure 1.2. (a) The Gran Sasso Massif; (b) The Municipality of Arsita (AQ)

2. THE SURVEY ACTIVITY

In a two-week stay in Arsita, a group of about twenty researchers and stage graduates (architects, structural engineers, geologists, Remote Sensing and GIS experts, art historians and other technicians) began a work targeted on the following topics: assess natural (mainly earthquake and landslide) and anthropogenic hazards, construction vulnerability (including earthquake damage, structural details, maintenance, materials features) and risk; perform in situ surveys (topography, landscape and land use analysis, urban planning and architecture, infrastructure, etc.); evaluate energy efficiency and sustainable techniques.

Thanks to the effective support of the Arsita Technical Office, several working tasks have been carried out during the team mission (Indirli et al., 2011):

1) *Acquisition and evaluation of cartographic and photogrammetric data*: a process, not completed yet, indispensable to build up all the GIS layers constituting the indispensable skeleton of the georeferenced database
2) *Analysis of historic documentation* found in the Municipality archive, as past earthquakes and landslides, urban planning modifications, and past interventions on important churches and palaces
3) *Topographic survey:* consisting in the measurement by DGPS (Differential Global Positioning System) of a set of points along the Arsita city centre main street in order to provide sharp geographic coordinates for the GIS database and anchoring positions for the parallel Laser Scanner investigation.
4) *Laser Scanner survey:* that allows to obtain CAD drawings (useful also for geometric survey and vulnerability analysis) from the Laser Scanner clouds of points. The survey interested the ancient tower ruins, because it should be restored with urgent priority, due to its precarious conditions, and the main street front façades, to provide data useful for the generation of a 3D model of the historic centre.
5) *Urban planning, architectonic, energetic, vulnerability analyses in the historic centre:* started with a detailed verification of all the historic centre structural aggregates, which have been divided in sub-aggregates, checking carefully and modifying, when necessary, the previous organization provided by the Municipality Technical Office.
6) *GIS database and building inventory*. All the data gathered during the in situ investigation and elaborated in the framework of the office and laboratory activities have been organized in a GIS digitized database and building inventory, with the aim to describe, analyze, question and represent all the different layers of the information.

The data acquisition has been based firstly on direct visual surveys of the external and internal parts of all the interested constructions, including the measurement of the main geometric characteristics and the assessment of structural parts (walls, floors, roofs, etc.), materials, construction details and techniques. Samples of the most important materials (stone, brick, mortar, etc.) have been collected, with the aim to perform characterization laboratory tests.

At the same time, the AeDES forms (2000) (evaluation of seismic damage and safety), filled up by the Civil Protection expert teams during the emergency, have been studied, verified and digitized. Moreover the urban planning, architectonic and energetic forms have been filled up in order to investigate buildings description and energetic aspects.

Afterwards, several seismic vulnerability and damage procedures have been applied, fully described in the next sections, and precisely:

1) the GNDT II Level vulnerability forms, both for masonry and reinforced concrete buildings (GNDT, 1999a; GNDT, 1999b);
2) a specific form for masonry aggregates already applied to other Italian historical centres (Formisano et al., 2011)
3) the FaMIVE methodology, for damage evaluation of isolated masonry construction (D'Ayala and Speranza, 2002).
4) the MEDEA handbook (Papa and Zuccaro, 2004), both for masonry and reinforced concrete buildings, in order to investigate the damage/collapse mechanisms of historic centre constructions under seismic actions.

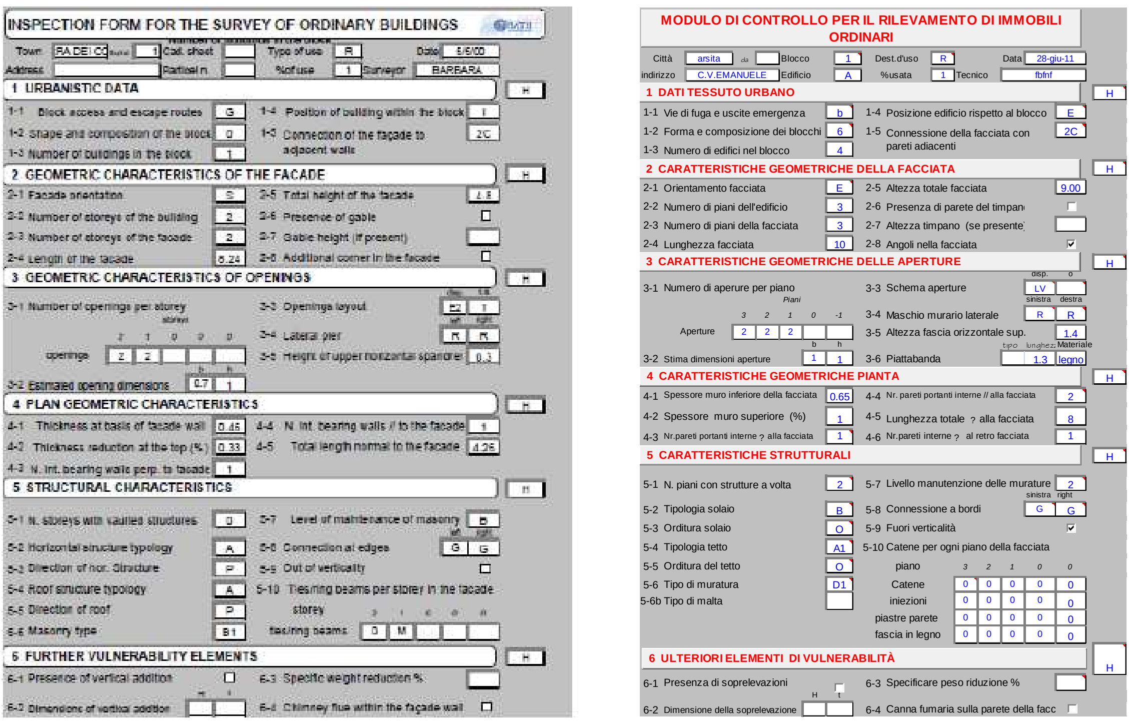
A particular attention will be paid to construction seismic vulnerability and damage, to be obtained comparing the results coming from various methods and procedures, because only the accurate knowledge of those aspects can lead to a correct definition of rehabilitation and reconstruction interventions.

Finally, the forms targeted on the description of the open spaces have also been filled up in order to complete the preliminary investigation.

3. THE USED SEISMIC VULNERABILITY ASSESSMENT METHODS

3.1. The FaMIVE procedure

The FaMIVE (*Failure Mechanisms Identification and Vulnerability Evaluation*) analytical method is an integrated procedure aimed at the seismic vulnerability evaluation of single buildings.
This procedure concerns the preliminary survey of the constructions to be examined, in order to collect their essential structural and geometrical data. In the survey phase, the identification of both the most vulnerable factors and the strengthening devices is performed, since the knowledge of these elements is very important for appraising the structural and seismic performance of buildings.
Data collected are, afterwards, stored and processed by means of a specific spreadsheet elaborated by the authors (Fig. 3.1a). A static equivalent analysis type is performed on the building and aims to calculate the lateral loads multiplier which trigger the onset of a specific failure mechanism. This factor, expressed as a percentage of the gravity acceleration, allows to predict possible damages and vulnerability levels for the analysed structure, in relation to the expected seismic intensity.
Two important innovative aspects of this technique must be highlighted: the procedure takes into account the out-of-plane failure mechanisms as possible causes of collapse and, furthermore, it permits to reduce the structural vulnerability by means of the introduction of specific strengthening devices. In particular, the program considers eight elemental out-of-plane collapse mechanism by means of the limit state analysis. Furthermore, it also takes into account the occurrence of local collapses, by achieving a storey by storey analysis.
An example of the analysis performed with FaMIVE within the historical centre of Arsita on each single façade of a generic building is shown in Fig. 3.1b.


INSPECTION FORM FOR THE SURVEY OF ORDINARY BUILDINGS
1 URBANISTIC DATA
1-1 Block access and escape routes
1-2 Shape and composition of the block
1-3 Number of buildings in the block
1-4 Position of building within the block
1-5 Connection of the façade to adjacent walls
2 GEOMETRIC CHARACTERISTICS OF THE FACADE
2-1 Facade orientation
2-2 Number of storeys of the building
2-3 Number of storeys of the facade
2-4 Length of the facade
2-5 Total height of the facade
2-6 Presence of gable
2-7 Gable height (if present)
2-8 Additional corner in the facade
3 GEOMETRIC CHARACTERISTICS OF OPENINGS
3-1 Number of openings per storey
3-2 Estimated opening dimensions
3-3 Openings layout
3-4 Lateral pier
3-5 Height of upper horizontal spandrel
4 PLAN GEOMETRIC CHARACTERISTICS
4-1 Thickness at basis of facade wall
4-2 Thickness reduction at the top (%)
4-3 N. int. bearing walls perp. to facade
4-4 N. int. bearing walls // to the facade
4-5 Total length normal to the facade
5 STRUCTURAL CHARACTERISTICS
5-1 N. storeys with vaulted structures
5-2 Horizontal structure typology
5-3 Direction of hor. structure
5-4 Roof structure typology
5-5 Direction of roof
5-6 Masonry type
5-7 Level of maintenance of masonry
5-8 Connection at edges
5-9 Out of verticality
5-10 Tie/ring beams per storey in the facade
6 FURTHER VULNERABILITY ELEMENTS
6-1 Presence of vertical addition
6-2 Dimensions of vertical addition
6-3 Specific weight reduction %
6-4 Chimney flue within the façade wall

MODULO DI CONTROLLO PER IL RILEVAMENTO DI IMMOBILI ORDINARI
Città arsita; Blocco 1; Dest.d'uso R; Data 28-giu-11
indirizzo C.V.EMANUELE; Edificio A; %usata 1; Tecnico fbfnf
1 DATI TESSUTO URBANO
1-1 Vie di fuga e uscite emergenza b
1-2 Forma e composizione dei blocchi 6
1-3 Numero di edifici nel blocco 4
1-4 Posizione edificio rispetto al blocco E
1-5 Connessione della facciata con pareti adiacenti 2C
2 CARATTERISTICHE GEOMETRICHE DELLA FACCIATA
2-1 Orientamento facciata E
2-2 Numero di piani dell'edificio 3
2-3 Numero di piani della facciata 3
2-4 Lunghezza facciata 10
2-5 Altezza totale facciata 9.00
2-6 Presenza di parete del timpano
2-7 Altezza timpano (se presente)
2-8 Angoli nella facciata
3 CARATTERISTICHE GEOMETRICHE DELLE APERTURE
3-1 Numero di aperture per piano
Aperture 2 2 2
3-2 Stima dimensioni aperture 1 1
3-3 Schema aperture LV
3-4 Maschio murario laterale R R
3-5 Altezza fascia orizzontale sup. 1.4
3-6 Piattabanda 1.3 legno
4 CARATTERISTICHE GEOMETRICHE PIANTA
4-1 Spessore muro inferiore della facciata 0.65
4-2 Spessore muro superiore (%) 1
4-3 Nr.pareti portanti interne ⊥ alla facciata 1
4-4 Nr. pareti portanti interne // alla facciata 2
4-5 Lunghezza totale ⊥ alla facciata 8
4-6 Nr.pareti interne ⊥ al retro facciata 1
5 CARATTERISTICHE STRUTTURALI
5-1 N. piani con strutture a volta 2
5-2 Tipologia solaio B
5-3 Orditura solaio O
5-4 Tipologia tetto A1
5-5 Orditura del tetto O
5-6 Tipo di muratura D1
5-6b Tipo di malta
5-7 Livello manutenzione delle murature 2
5-8 Connessione a bordi G G
5-9 Fuori verticalità
5-10 Catene per ogni piano della facciata
6 ULTERIORI ELEMENTI DI VULNERABILITÀ
6-1 Presenza di sopraelevazioni
6-2 Dimensione della sopraelevazione
6-3 Specificare peso riduzione %
6-4 Canna fumaria sulla parete della facc

(a) (b)

Figure 3.1. (a) The FaMIVE general survey form; (b) application of the form (in Italian) to a building in Arsita

3.2. The GNDT II level methodology

The quick GNDT II level procedure was developed in the area of the activities of GNDT (National Group for Defence from Earthquakes) over the last twenty years.
The GNDT II level method is based on the original Benedetti and Petrini’s form (1984), commonly

used for vulnerability assessment on local and large scale of masonry and r.c. buidlings.
Therefore, the GNDT II level approach is an expert judgement based technique aiming at the estimation of the seismic vulnerability of buildings by means of the calculation of an appropriate vulnerability index I_v. This index is assigned to each examined construction after a visual inspection aiming to identify the primary structural system and the significant seismic deficiencies.
The GNDT II level form has been developed by individuating eleven parameters recognised as the most important factors in controlling building seismic behaviour. Each parameter is differentiated into four classes, indicated with A, B, C and D (in increasing order of vulnerability), having a score *s* changing from 0 (class A) to 45 (class D). A given weight *w* is finally assigned to each vulnerability factor aiming at highlighting the most significant parameters in determining the structural behaviour toward earthquakes.
So, the vulnerability index *Iv* is calculated by summing the different scores and the relative weights attributed to these parameters, according to the following equation:

$$I_v = \sum_i s_i \cdot w_i \quad (3.1)$$

The index I_v ranges from 0 to about 382, which is the upper index obtained by the assignment of the maximum score to each factor. The index may be also eventually normalised as respect to the maximum value. So a value from 0 (best vulnerability condition) to 100 (worst vulnerability condition) is achieved.

3.3. A vulnerability form for masonry building aggregates

The seismic behaviour of a building within a masonry block is different from the response of the same building considered as isolated, since several aspects of the aggregate condition can improve or increase its seismic vulnerability.
In Formisano et. al (2009), a new procedure for seismic vulnerability evaluation of masonry blocks has been proposed in order to estimate the vulnerability of structural units having behaviour conditioned from the presence of adjacent buildings. This methodology is aimed at satisfying the necessity to setup a quick technique for vulnerability assessment through simplified analyses based on the structural and geometric characteristics of buildings. The data to be collected during the survey are reduced to meaningful information, just those which can qualify the seismic performance of masonry buildings. In particular, this methodology starts form the previously described procedure implemented by Benedetti and Petrini (1984) for isolated masonry constructions.
In order to take into account the effect of adjacent buildings on the seismic performance of a given masonry building grouped into aggregate, the proposed procedure introduces five additional factors to the original form implemented by Benedetti and Petrini. These performance modifiers are: 1. presence of adjacent buildings with different height; 2. position of the building in the aggregate; 3. presence and number of staggered floors; 4. effect of either structural or typological heterogeneity among adjacent structural units; 5. difference of the percentage of openings among adjacent facades.
Similarly to the Benedetti and Petrini's form, all these features are differentiated into four classes (A, B, C and D). Score and weight values have been assigned to these factors according to a previous study (Formisano et. al, 2009), where parametric analyses on a structural unit inserted within a masonry aggregate typical of the urban nucleus of Sessa Aurunca, a small town close to Caserta, have been performed by means of the 3MURI software. The achieved results have been further validated on other Italian historic centres, especially on some of them damaged by the 2009 L'Aquila earthquake (Formisano et al., 2011). Therefore, as in the original method, a synthetic vulnerability index is achieved as a sum of the different scores multiplied by the respective weights. The proposed new form is shown in Table 3.1, where the five additional parameters are placed on a grey background.

Table 3.1. New proposed form for seismic vulnerability assessment of masonry building aggregates

Factors	Class score (s)				Weight (w)
	A	B	C	D	
Organization of vertical structures	0	5	20	45	1.00
Nature of vertical structures	0	5	25	45	0.25
Location of the building and type of foundation	0	5	25	45	0.75
Distribution of plan resisting elements	0	5	25	45	1.50
Plan regularity	0	5	25	45	0.50
Regularity in elevation	0	5	25	45	0.50÷1.00
Type of slabs	0	5	15	45	0.75÷1.00
Roofing	0	15	25	45	0.75
Details	0	0	25	45	0.25
Physical conditions	0	5	25	45	1.00
Presence of adjacent buildings with different height	-20	0	15	45	1.00
Position of the building in the aggregate	-45	-25	-15	0	1.50
Presence and number of staggered floors	0	15	25	45	0.50
Effect of either structural or typological heterogeneity among adjacent structural units	-15	-10	0	45	1.20
Percentage difference of openings among adjacent facades	-20	0	25	45	1.00

3.4. The MEDEA handbook

MEDEA (in Italian: *Manuale di Esercitazioni sul Danno Ed Agibilità*) is a multimedia and didactic handbook for seismic damage evaluation and post-event macroseismic assessment of r.c. and masonry structures. MEDEA is organized as an electronic database structured in different sections and represents a guided training path for usability evaluation of damaged buildings.
The first section concerns a glossary (Fig. 3.2) of the main terms frequently used in technical and scientific field; some pictures and graphics, a descriptive text and links to other terms in the glossary correspond to each term of the dictionary. All the terms are organized into the following five categories: 1) structural elements of constructions; 2) structural seismic damages; 3) yard equipment in the emergency; 4) provisional interventions; 5) environment.
The MEDEA second section consists of an archive of pictures showing different structural typologies and different levels and types of damages (Fig. 3.2).

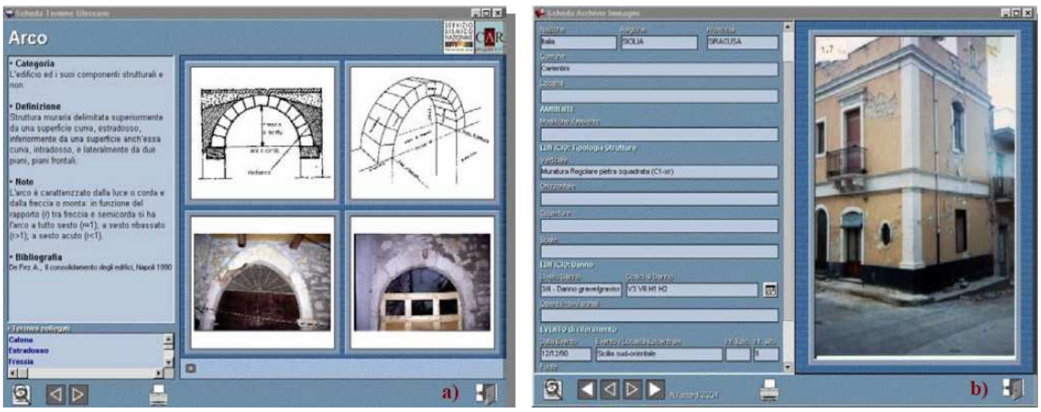


Figure 3.2. The MEDEA glossary and archive

The most important part of MEDEA is constituted by a detailed catalogue of the main damages on structural and no structural elements of buildings. This damage classification is used for interpreting the detected collapse mechanisms.
The catalogue is constituted by three sub-sections:

1. *Collapse Mechanisms Abacus*, in which the main recognisable collapse mechanisms for a

standard structure are classified.

2. *Damages Abacus*, in which the main damages that a building may suffer under seismic actions are classified and described into a specific form.
3. *Interactive Training*, a table where to each kind of damage selected by the user is associated to a possible collapse mechanism congruent to the chosen damage.

The first part defines global and local failure mechanism. Generally, global mechanisms are those involving the whole structure such that the evolution of the cracks compromises the structural static and dynamic equilibrium, while local mechanisms pertain marginal parts of the structure and generally do not involve the whole structural equilibrium.

In particular, for masonry structures, the structural global mechanisms are subdivided as follows:

- *in-plane mechanisms*, that occur when the classical diagonal cracks due to the poor tensile strength of masonry material are formed in the piers;
- *out of plane mechanisms*, that may occur when out-of-plane kinematics of one or more walls of the masonry box are activated, generally due to the connection deficiency between the facade walls and the walls orthogonal to them;
- *other collapse mechanisms*, classified as those mechanisms that could not directly be recognised as in-plane or out-of-plane, even if they are able to cause the total structural collapse of the structure.

The local mechanisms are, instead, due to:

- localized dislocation (e.g. arch or architrave failure);
- presence of pushing elements: the mechanism is determined by the action of single elements that produce horizontal actions on supporting structures.

A resumptive scheme of global and local mechanisms is shown in Figs. 3.3 and 3.4.

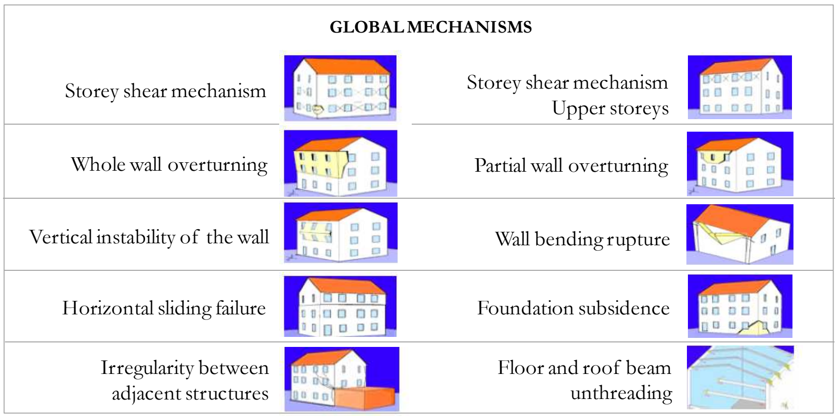


Figure 3.3 Abacus of the global collapse mechanisms

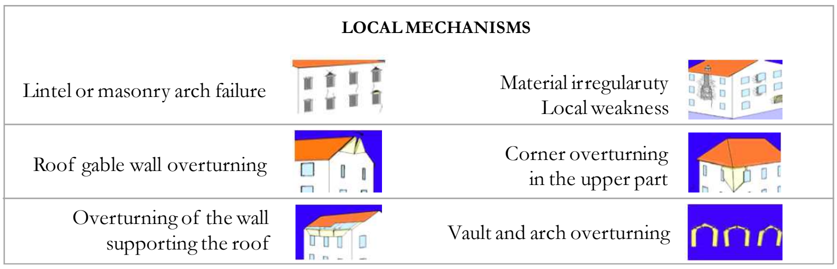


Figure 3.4. Abacus of the local collapse mechanisms

The training section is the final part of the MEDEA handbook, in which some examples related to the damage and vulnerability assessment of buildings are shown (Fig. 3.5). This activity allows to identify, for some constructive typologies, the global damage of building, as well as the damage of its constitutive elements, leading to its safety assessment and providing possible provisional interventions to be adopted.

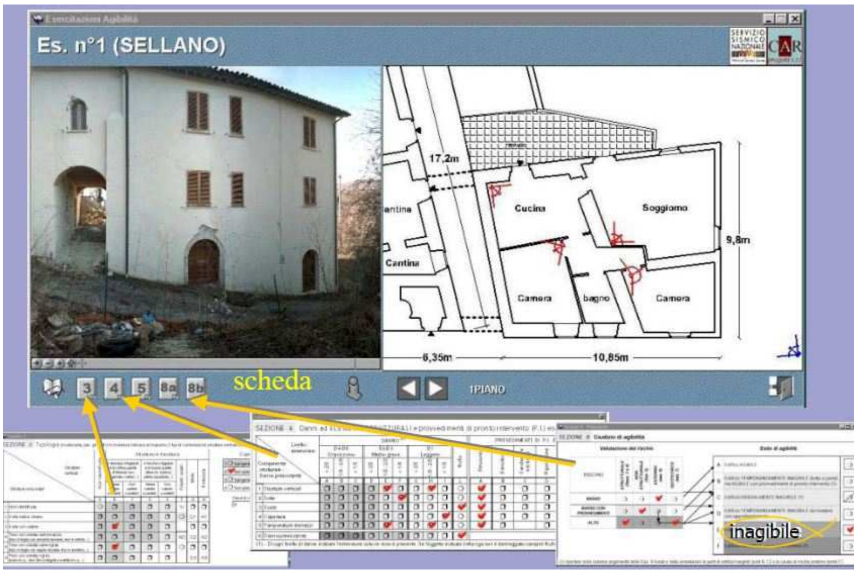


Figure 3.5 MEDEA training section

4. THE DAMAGE MECHANISM SURVEY

The present section focuses the attention on the damage evaluation detected in the historical centre of Arsita during the survey activity. The in situ investigations of masonry buildings have, indeed, revealed important failure patterns into both vertical and horizontal structures.

Firstly, in the post-earthquake management, a quantitative damage description was performed by using the AeDES form procedure (2000). Thus, the safety checks have generally provided high risk for both structural and non-structural elements, so that all surveyed buildings have been evacuated. Subsequently, among the mentioned analysis procedure, the MEDEA form has been firstly applied in order to obtain more information about the damaged structures and, therefore, to make hypotheses about both the damage genesis and their structural performance under seism. As a result, the following main collapse mechanisms, numbered as in the MEDEA form, have been identified and correlated to possible vertical (V) and horizontal (H) damages:

- *Global in-plane mechanisms*, consisting of storey shear failures (types 1 and 2; Fig. 4.1), due to diagonal shear cracks in the masonry piers (V1);
- *Global out-of-plane mechanisms*, characterised by either whole or partial wall overturning or walls bending collapse (types 3, 4 and 6; Fig. 4.2), triggered by vertical cracks at the wall corners (V9);
- *Local mechanisms*, especially consisting of local weakness, corner overturning in the upper building part and local cracks (Fig. 4.3);
- *Horizontal damage*, characterised by either whole or partial wall crushing due to the floor beams (H11) (Fig. 4.4).

Figure 4.1. Global in-plane mechanisms

Figure 4.2. Global out-of-plane mechanisms

Figure 4.3. Local mechanisms

Figure 4.4. Horizontal failure mechanisms

The next study phase will consist on the application of other cited vulnerability assessment methods in order to both justify the detected damage mechanisms and evaluate the real vulnerability of examined buildings through the comparison of achieved results.

4. CONCLUSIVE REMARKS

In the paper the technical scientific activities performed in the historical centre of Arsita until now have been presented. These activities have been consisted in the assessment of the construction vulnerability, including earthquake damage, structural details, maintenance and materials features evaluation, by performing in situ surveys.
The described survey represents only the first step of a more complex work, where the comparison of results achieved by applying the mentioned vulnerability evaluation procedures will allow to identify the real susceptibility at seismic risk of investigated building, permitting also to define a ranking of methods in predicting the damage suffered by buildings under earthquakes aiming at implementing a unique and effective global evaluation procedure.
The research activity will be completed within the next summer by a multidisciplinary team in the framing of the achievement of the historic centre reconstruction plan, which is going to be entrusted under the coordination of ENEA. The plan, which will be realised by means of a specific agreement with the Arsita Municipality, is aimed at the proposal of guidelines on urban planning, structural intervention and sustainable development, based on the definition of mitigation actions and urban habitat rehabilitation strategies, avoiding conflicts with the criteria of cultural heritage conservation.

ACKNOWLEDGEMENTS
First of all, we want to thank the Mayor of Arsita, Enzo Lucci, the Administration, and all the Technical Office personnel, for the great support given to the team during all the work, which is the best auspice for the future development of the activities.
A special thank goes also to the Arsita population for the warm and friendly support given.

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