SEISMIC VULNERABILITY ANALYSES OF MASONRY AGGREGATE BUILDINGS IN THE HISTORICAL CENTRE OF SULMONA (ITALY)

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ABSTRACT

The limit analysis approach applied to structural macro-elements that can develop in historical masonry buildings under seismic action, depending on few geometric and mechanical parameters, allows reliable expeditious vulnerability assessments. Vulnus is an automatic procedure developed at the University of Padova and based on numerical models calculating the accelerations which activate local collapse mechanisms of macro-elements: the methodology provides, through a knowledge based fuzzy model, vulnerability assessments of individual structural units or groups of buildings, as well as fragility curves related to the achievement or overcoming of the limit state of heavy damage. Moreover, Vulnus is able to identify the vulnerability class for each structural unit, as defined by the European Macroseismic Scale EMS98, allowing the construction of damage scenarios. The EMS98 scale separates the definitions of building typologies from the corresponding vulnerability class and thus from the expected behaviour in case of seismic event: in this way, it provides a common framework for the evaluation of seismic vulnerability and the estimation of the damage of buildings on a large scale.

The results of analytical applications of the procedure on buildings aggregates sampled in the historic centre of Sulmona, in L'Aquila province, an important historic centre in Central Italy, are presented. It is an area of great interest, not only considering its seismic history, but also because of the characteristics of its prestigious buildings, mainly made of poor multiple leaf stone masonry.

Preliminarily, an on-site investigation methodology, based on the buildings survey using specific forms, the collection of data on interventions, damage mechanisms, etc. and a minimum number of laboratory and in-situ tests, was applied in order to collect all the data requested by Vulnus and to provide useful indications on the actual vulnerability conditions of the centre to be compared with the results obtained with the automatic procedure. In fact, the knowledge of typology and damage of historic masonry structures in seismic area is fundamental for the choice of suitable techniques and materials aimed to the preservation and damage prevention of the cultural heritage. The paper describes this procedure, addressed to an articulated knowledge of the material, of the morphology and of the constructive aspects of the masonry structures, of the mechanical behaviour and of the possible failure mechanisms of complex buildings in Sulmona (AQ). The understanding of the historical buildings has made use of a direct survey of the constructions (based on a geometrical survey, on a survey of the materials and of their state of damage), of indirect information deduced by documentary sources, and of data collected through in-situ non destructive or minor destructive testing and laboratory investigation for a chemical, physical and mechanical characterisation of the masonry and of its components.

INTRODUCTION

The empirical observation of the damages caused to buildings by earthquakes of medium or high intensity highlighted that buildings subject to the same seismic excitation show radically different behaviour, related to their typology, construction rules, used materials and maintenance level. In case of complex buildings, that are the result of subsequent changes, the analyses of the historic centres need a proper structural modelling: this is necessary in order to appraise the specific vulnerability of complex buildings, due to their typical historical evolution (constructive sequence, damages, previous interventions, etc.).

Since the 80s in Italy, empirical evaluations, by the so called "vulnerability indexes" (particularly for masonry buildings (Benedetti & Petrini, 1984), have been proposed, based on weighted sums of vulnerability factors, related both to structural irregularity aspects recorded by rapid systematic or sample surveys and to the actual calculations of the resistance to horizontal actions of the masonry walls. The aim was to compare the vulnerability of different buildings (and thus the priorities for strengthening operations), and to provide damage scenarios for different seismic intensities.

The available structural analysis methods for masonry buildings subjected to static and dynamic actions are reflected in codes: their application is allowed both for the design of new buildings and for the analysis of existing ones. Through these methodologies, transferred in easily accessible automatic procedures, it is possible to achieve fragility curves of buildings: these curves represent the state of damage, or the likelihood of damage, on the basis of objective measures of the seismic shaking, e.g. peak acceleration of ground motion (PGA).

Within these methodologies and with specific reference to historic masonry buildings, some procedures have been proposed: they are based on the identification of the values of horizontal static-equivalent forces (and therefore of the values of the masses accelerations) that can activate specific mechanisms of local failure / overturning of structural macro-elements (composed by single walls or subassemblages, as intersecting walls, walls and floors or roof, etc.) in-plane and, especially, out-of-plane. In these buildings, in fact, the absence of systematic connections between intersecting walls and between walls and horizontal structures may cause kinematic mechanisms related to the loss of equilibrium of structural portions rather than to states of stress exceeding the materials ultimate capacity (Giuffré & Carocci, 1999); this limit analysis approach depends on few geometric and mechanical parameters and therefore it does not require an extremely accurate survey and time-consuming computation. Moreover, these calculation models process the inevitable uncertainty of the prediction by the use of appropriate numerical techniques that take into account the lack of sufficient information in calibrating probabilistic methods (this problem makes often illusory the precision of complex linear or nonlinear behavioural models) (Bernardini, 1999).

In the last years, the authors have studied and proposed methodologies for the assessment of the seismic vulnerability of buildings based on the limit analysis. The paper discusses the main results of the application of one of these procedures to the historic centre of Sulmona (in the province of L’Aquila - Abruzzo region), located in a site in current hazardous conditions.

A reliable investigation methodology was applied on this centre: it is based on the on-site survey of a significant sample of buildings using specific forms, the collection of data on interventions, damage mechanisms, etc. and a minimum number of laboratory and on-site (non-destructive and minor destructive) tests, realized in order to characterize the texture, the structure and the materials of the investigated walls (Binda et al., 2007). This general methodology allowed to gather all the data requested by the Vulnus procedure. In fact, the analysis suggested by the present Italian Seismic Code (NTC 2008) for the knowledge of existing buildings is considered excessively heavy for the intervention on single buildings, especially if it rises within an aggregate, a very common condition in historical centres. A compromise is therefore necessary between what it is reasonably demanded to a designer and what is essential from an exhaustive knowledge point of view. The problem can be faced by a method that can be easily applied through record templates and forms and allows the strength and vulnerability characteristics of a building to be individuated, which are crucial towards the structural seismic response.

A multi-level procedure has been set up and applied here to study complex buildings in the historical centre of Sulmona. The investigation method adopted by the Authors since the beginning of the '90s (Binda et al., 1999) is based on the principle that knowledge is fundamental for the choice of suitable techniques and materials aimed to the preservation and damage prevention of the cultural heritage.

This procedure has been well calibrated in different on site investigations on historic masonry buildings in the Umbria region after the earthquake of 1997 (Binda et al., 2004), in the Liguria region (Anzani et al., 2004) hit by earthquakes in the 19th century, in the area of Garda Lake involved in the earthquake of 2004 (Anzani et al., 2007; Cardani et al., 2008). The earthquake that struck Umbria and Marche regions in 1997 gave the occasion to learn that the lack of knowledge on the material and structural behaviour of the existing buildings was, and still is, the main cause of inappropriate choices of the intervention techniques. The problem of repair and retrofitting should be approached in a multidisciplinary way, considering different complementary aspects including: historical evolution of the buildings, geometry and crack pattern, material characteristics, technology of construction, possible failure mechanisms, etc (Penazzi et al., 2000; Binda et al., 2003). To this respect, the collaboration between architects/"restorators", historians, structural engineers is particularly important. As previously said, all the collected complementary data will allow an interpretation of the structural response which takes account of the examined masonry and building typology, leading to evaluate the seismic vulnerability and to define reliable retrofitting procedures of stone-masonry buildings.

SHORT STUDY OF THE HISTORIC CENTRE OF SULMONA

The first phase of the research presented here consisted of a study of the historical centre of Sulmona aimed to understanding the rules of the formation and growing of the built types, starting from the first construction until the fusion and complex additions of new bodies. The city was founded by the Romans and had a subsequent development in Medieval time. In Figure 1 its more recent evolution is shown where it appears that the main part of the edification has been mostly carried out before 1800. After collecting historical information on the evolution of the ancient city centre, the elements having structural relevance are analysed.

Diffuse architecture, often poorly constructed, is mainly composed of stonework buildings with timber roofs and floors. In spite of the use of apparently similar material and construction techniques, building characteristics vary according to their typology – from isolated to arrayed buildings – and to their location – from flat to steep mountain sites. This variety is directly connected to the orographical profile of the site and also to the common seismic history.

The recognition of the building typologies and of the characteristic constructive elements is a fundamental aspect aimed to their typo-morphological classification and to the creation of a catalogue of the constructive elements characteristic of the local architecture.

The importance of recognizing different building typologies, in view of the definition of their seismic vulnerability, depends on the correspondence between construction typologies and mechanisms of damage. Considering complex cases as for the geometry and original destination, it has to be pointed out that any typology, for instance palaces, religious buildings, towers, castles, fortifications, churches, etc., display specific problems, also connected to the function of the building itself. Such differences, that have influenced the original constructive solutions and the wall masonry quality, similarly will influence the safety assessment and the techniques of intervention. Therefore, for any typology, the matter should be to individuate and manage specific level of investigation, modelling, verification and specific repair techniques, satisfying also the function requirements.

In Figure 2 the location of buildings erected in 20th century, together with that of historical building typologies have been mapped, consisting of simple and double lines, simple and articulated blocks, open and closed courtyards, palaces and churches. It appears that the area of the city centre is mainly occupied by articulated blocks and also that many churches are present. Most of the buildings denominated "palaces" resulted from the evolution and the fusion of different residential units initially conformed as simple or double lines, mainly during the XVI century, improved through inner courtyards and decorative apparatus.

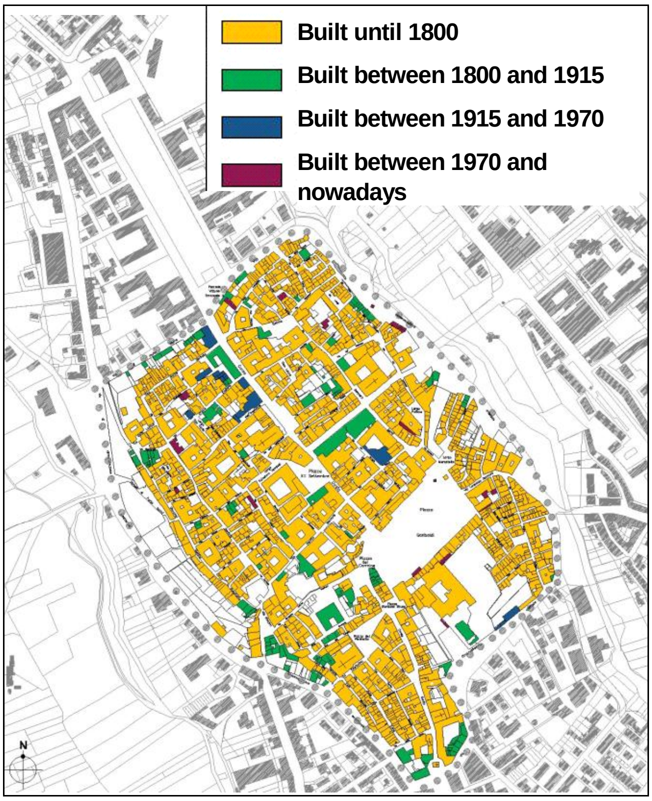


Figure 1: Historic evolution of the historic centre of Sulmona.

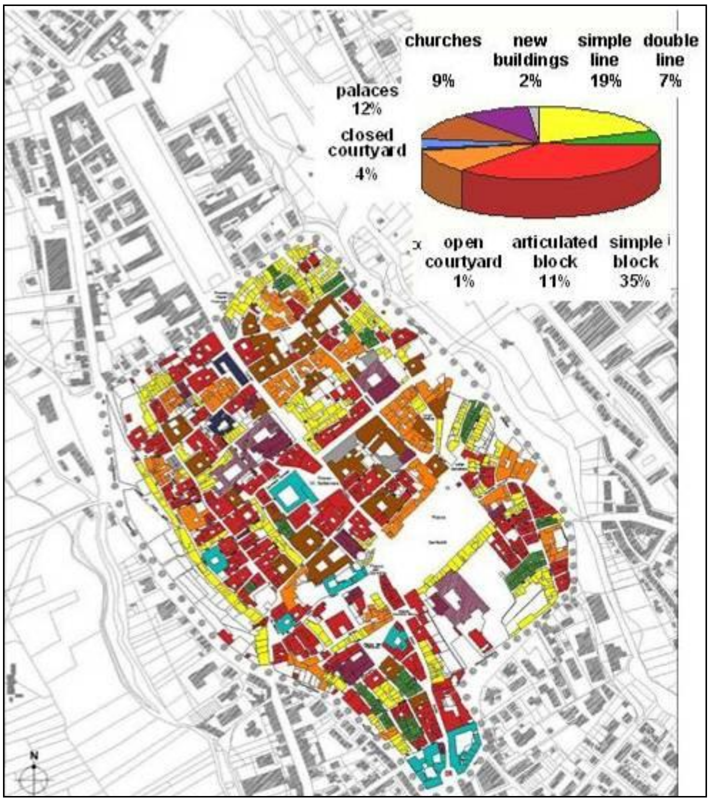


Figure 2: Distribution of building typologies in the centre of Sulmona.

Subsequently, a template aimed to the "Masonry quality evaluation" was adopted and applied to selected buildings characterized by facades with no plaster finishes, therefore having their stonework masonry texture available to visual inspection (Figure 3).

The prediction of the seismic vulnerability of stonework masonry, and particularly of the multiple wythe one, can only be performed provided the intrinsic characteristics of the masonry have been accurately detected. The behaviour of masonry highly depends on the construction technique and this is shown from the section layout. In fact, the outer face frequently does not reveal how the masonry section is built since apparently similar facing textures (e.g. regular bonding) may correspond to different types of sections, as one or multiple wythes. A systematic study of the mechanical behaviour of stonework masonry begins from an extensive investigation taking into account the different layers constituting the wall and the kind of constraints which may or may not exist between the layers themselves. From the analysis of this information, constitutive laws for modelling the masonry behaviour and for designing possible repair interventions (e.g. injection of grout) can be selected. Input data for the structural analysis with numerical methods are the section survey and the type of connection between the layers. These features can also be taken into account when modelling the in-plane or out of plane failure mechanisms.

Most of the historical buildings in Sulmona turn out to be characterized by three leaf stonework masonry (Figure 4-a). Considering the masonry textures on the wall facades, they mainly consist of disordered rubble stone rubble (according to table C8A.2.1 of the Italian Seismic Code - NTC 2008), always of calcareous nature, with friable mortar. The observed textures are generally made of irregular and sub-horizontal courses, in few cases of regular ones, and with unfinished or partially finished stone blocks. The stone interlocking on the outer face is generally low or very low, in few cases medium (Figure 4-b). In general the masonry quality, evaluated by visual inspection, turns out to be scarce. On some of these buildings, also a second template aimed to the "Typological and seismic damage survey of buildings" (Binda et al., 2000) and the evaluation of their vulnerability was applied.

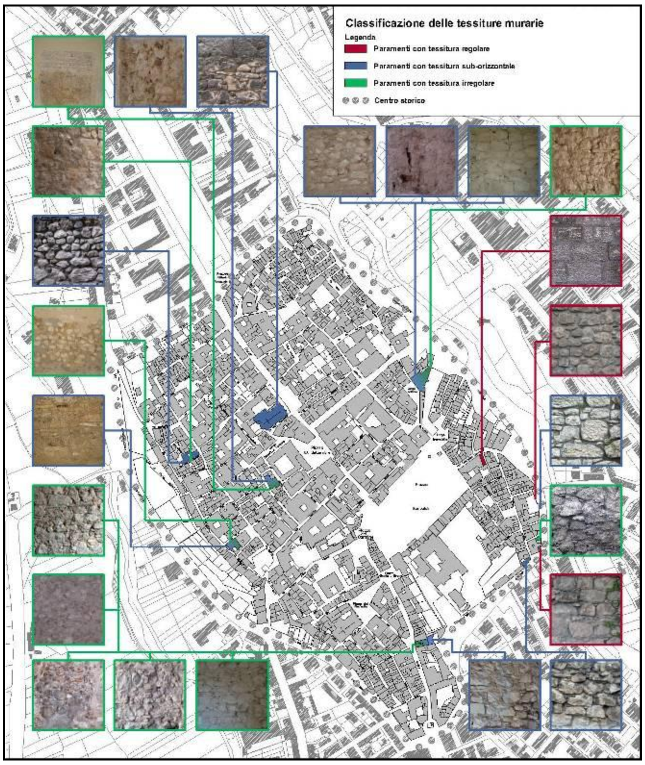
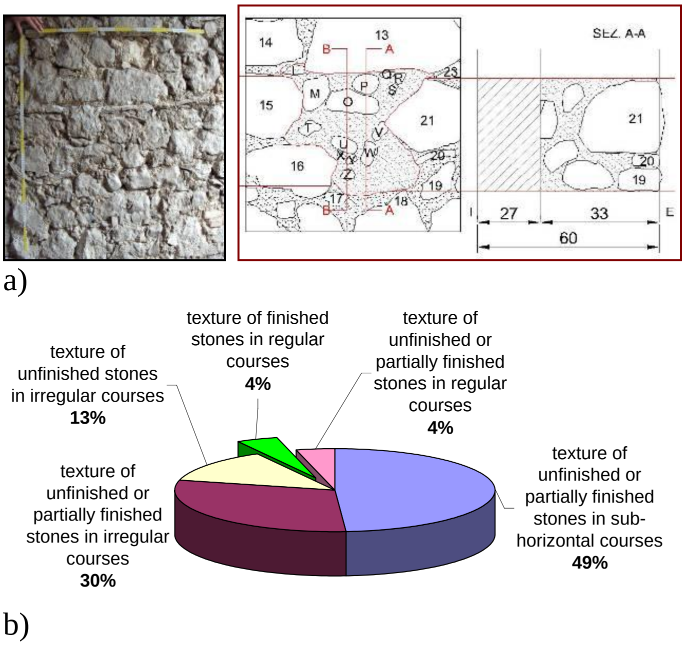


Figure 3: Location of the surveyed buildings showing masonry façades in the historical centre of Sulmona.



a)

b)

Figure 4: a) Three-leaf masonry section on block 39 in Ovidio street; b) masonry classification of the textures and manufacture observed.

DIRECT INVESTIGATION ON SELECTED BUILDINGS

Significant aggregates were identified (painted blue in Figure 3) and subjected to a systematic investigation which included the following phases: (i) geometrical survey of the building and of its crack pattern, (ii) interpretation of the crack pattern and definition of the damage or collapse mechanisms affecting each building, (iii) detection of the connections between walls and between roofs and vaults to walls, (iv) non destructive evaluation of damage, (v) survey of the masonry texture and of the morphology of the wall sections, (vi) on site characterisation of the masonry walls through sonic and flat-jack tests, (vii) sampling and laboratory characterisation of mortars, plasters and stones through chemical, physical and mechanical tests.

Aggregates of historical buildings have generally been subjected to the addition of several volumes in different times, and the possible discontinuities between the different volumes could affect the overall seismic behaviour. In Figures 5 and 6 block 69 in Acuti street is shown as an example. Its volume was apparently rather simple when looked from the outside, whereas required to be subdivided into three macro-elements once surveyed in more detail (Figure 7). For a reliable interpretation of the signs of damage, the preliminary in-situ survey, useful to obtain details on the geometry of the structures, identifying irregularities like vertical deviations, rotations, etc. needed complementary indication coming from the investigation of the historical evolution of the structure in its complexity.

On the chosen case studies, significant walls were recognized for a complete characterization of the masonry where the following tests were systematically carried out: (i) sonic tests by transparency on a grid of 75 x 75 cm for measurement of the sonic velocity, (ii) single and double flat-jack tests for measurement of the state of stress, the modulus of elasticity and the coefficient of lateral expansion, (iii) survey of the masonry morphology and material sampling for characterizing the mortar and stones chemical, physical and mechanical properties, (iv) repositioning of the stones in the wall, with compatible mortars.

In Figure 8 the results of sonic tests on a pillar rising at ground floor of block 69 are reported. It is interesting to observe the agreement between the distribution of sonic velocity, with higher values corresponding to the outer portions of the pillar and lower values at mid span, and the crack pattern, showing cracks running where the lower velocity has been recorded.

After in situ and laboratory characterization and a 3D evaluation of the crack pattern, the main weakness characteristics towards the building seismic response were singled out. In fig. 9 the presence of a standing out body and a room with the lack of the floor are indicated as an example.


a) b)

Figure 5: Location and views of the simple block 69 in Acuti street: a) view from outside and b) particular of the internal court.

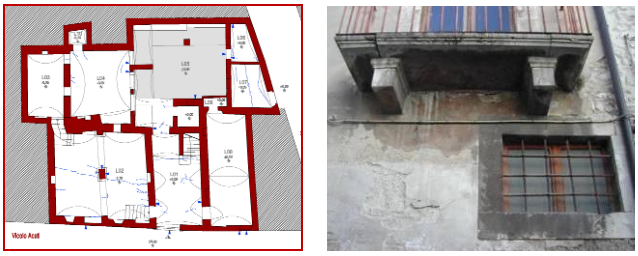

a) b)

Figure 6: a) Ground floor of block 69 and b) detail of the façade with the openings modifications over time.

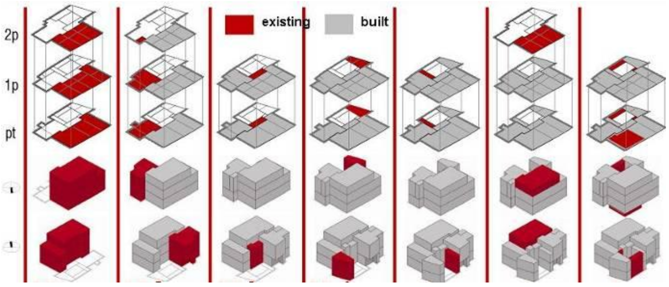


Figura 7: Hypothesis of the historical evolution of block 69.

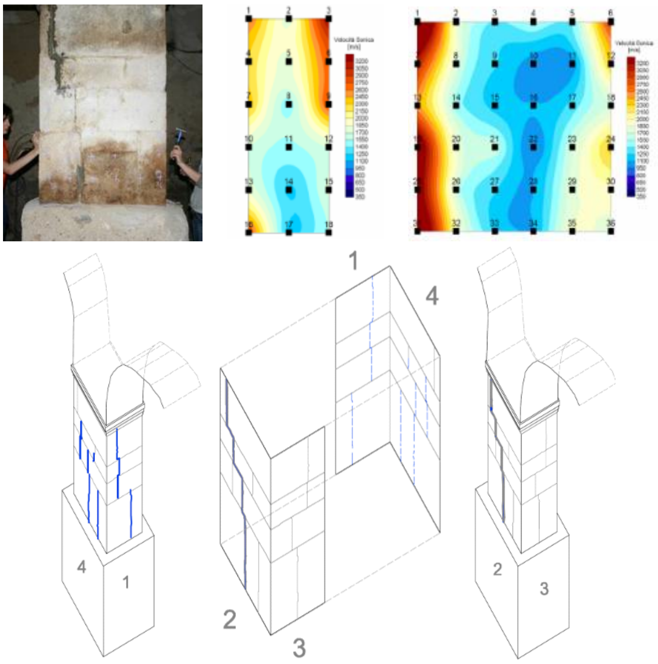


Figure 8: Sonic pulse velocity maps and study of the crack pattern of a pillar at ground floor of block 69.

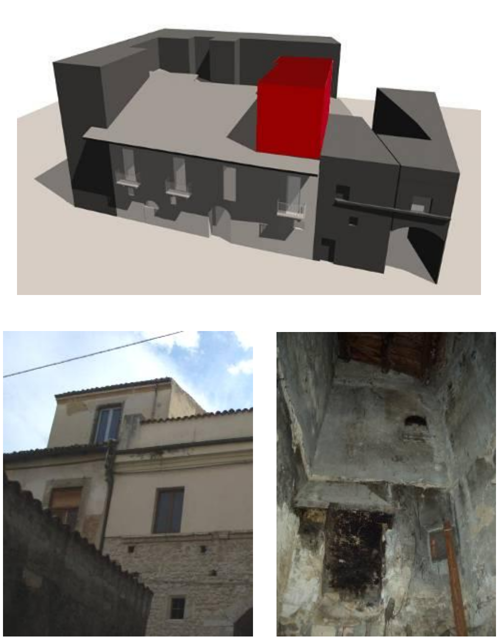
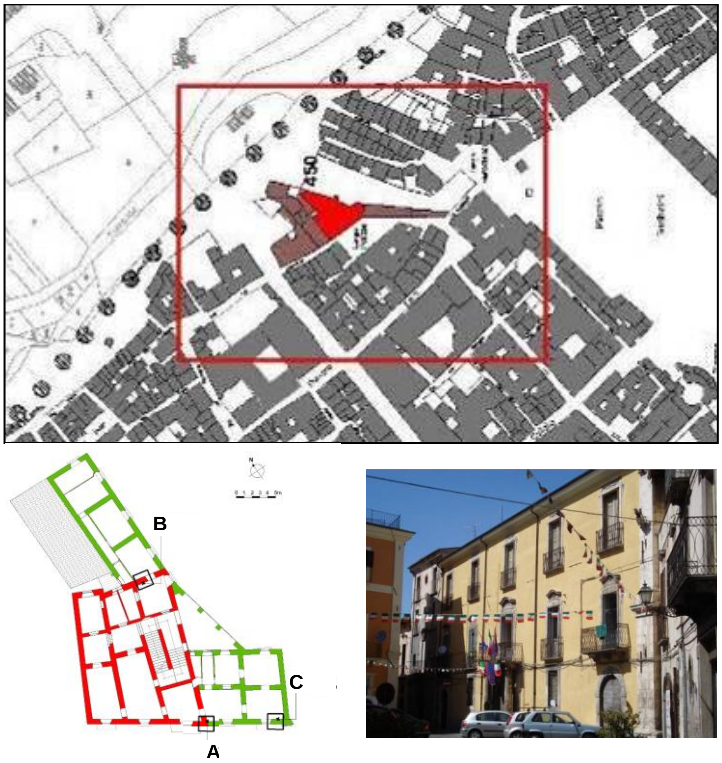


Figura 9: Weaknesses in block 69: standing out body and lack of floor.

An other case study, Sardi Palace, is presented in Figure 10 (Binda et al., 2009), where on the plan of the building aggregate different colours indicate two constructive phases and capital letters refer to the testing points. Corresponding to point A, where parts of the building erected in different years converge, the masonry inspection after plaster removal highlighted that stone interlocking was absent (Figure 11) and therefore that the two walls presented no connections. Results of sonic and flat jack characterization of a wall located in the more recent part of the complex are reported in Figures 12 and 13. The results of in situ testing gave a confirmation of what was observed by visual inspection. The masonry quality resulted generally scarce, characterized by low values of sonic velocity; in some cases flat jack tests encountered difficulties to be applied, and indicated very high values of both vertical and horizontal displacements.



🟥 Original parts 🟩 Extension present since XIX cent.

Figure 10: Sardi Palace in Polizze square.

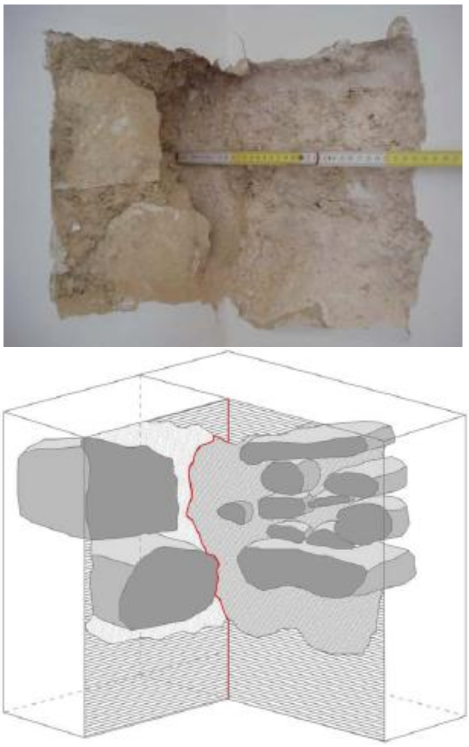


Figure 11: Survey of the wall interlocking on a corner of Sardi in Palace.

The survey of the morphology of the wall cross section was aimed to understanding whether the masonry was made of one or more leaves and whether the leaves were connected in some way. It was carried out by hammer and chisel, taking off some stones in order to visually investigate the wall texture, sketch the inner aspect of the wall and sample stones and mortars for laboratory testing. This inspection was useful to define the cross masonry section: three-leaf masonry, low adhesion between materials and no interconnection between the stone elements.

The mortars were submitted to chemical and physical analyses. The binder was separated from the aggregate by thermal attack and the grain size distribution was measured. The aggregate is mainly calcareous as well the binder being hydrated lime. The stones belonged to several litho types but limestone is the most frequent one.

STRUCTURAL MODELS

Lessons learned from recent earthquakes in Italy and in particular from the 1997 Umbria-Marche seismic event allowed to deepen the knowledge of the behavioural peculiarities of existing masonry buildings, in order to develop a general framework of vulnerability and forecasting, especially for “minor” centres and buildings typologies.

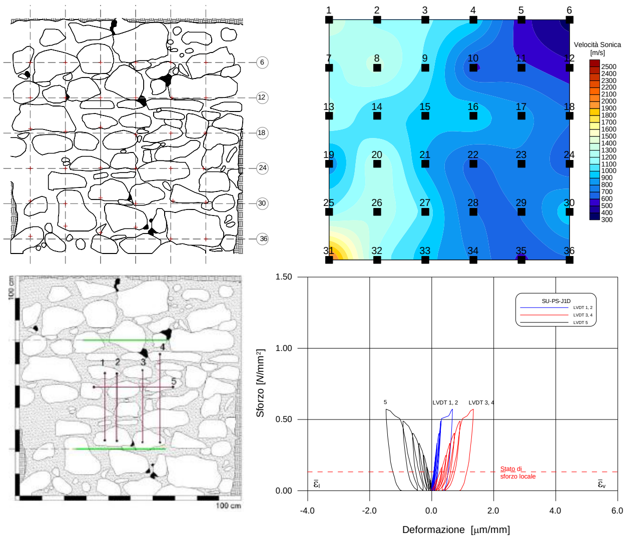


Figure 12: Results of the sonic pulse velocity and flat-jack tests on the original parts of Sardi Palace.

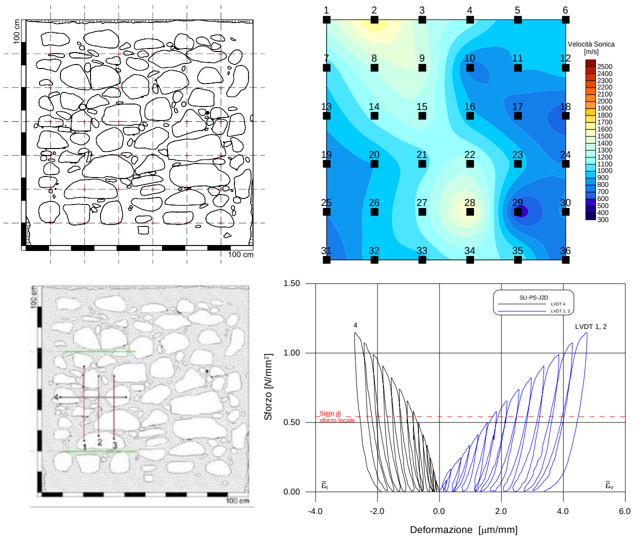


Figure 13: Results of the sonic pulse velocity and flat-jack tests on the extended parts of Sardi Palace.

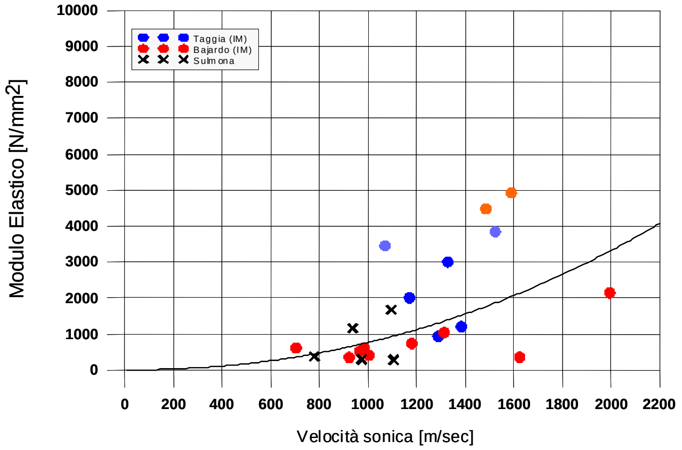


Figure 14: Relationship between E measured through double flat jack test and sonic pulse velocity.

Common buildings in historic centres were often built following a traditional “code of practice” and according to typologies (multi-material masonry, multi-leaf walls) and constructive details (in particular poor connections) which, in some cases, can show important deficiencies for the safety under seismic actions (Valluzzi et al., 2001).

Under these conditions, the ultimate capacity of the building depends on the stability of its macro-elements. Macro-elements are defined by single or combined structural components (walls, floors and roof), considering their mutual bond (potential damage pattern, cracks, borders of poor connections, etc.) and restraints (e.g. the presence of ties or ring beams), the constructive deficiencies and the characteristics of the constitutive materials. They behave independently as a whole without any support by other portions of the building, but they follow kinematic mechanisms, both out- and in-plane. Thus they are elements in hazardous conditions for possible incipient brittle collapse (Borri et al., 1999).

Out-of-plane mechanisms, also called “first-way” collapses, involve walls subjected to horizontal actions orthogonal to their plane. Their overturning is the main result, which is counteracted by the possible presence of connection elements (ties, ring beams) or intrinsic resisting effects (e.g. arch effect of the wall in its thickness). The proposed analysis method is based on equilibrium equations which can take into account also the strength of the materials (as well crushing of masonry, tension in the tie, etc.).

In-plane mechanisms relate to walls parallel to the seismic action. They are also named “second-way mechanisms”, because the relative damage (shear cracks), generally does not lead the structure to collapse, in comparison with the out-of-plane mechanisms. Kinematics chains describe the in-plane rigid rotation of the resisting structural portions of the building, defined by particular geometrical (dimensions of septa, openings) and bond conditions (connections, presence of ties), subjected to in-plane horizontal actions.

Once the critical structural configuration is defined, the subsequent step is the identification of the most probable collapse mechanisms of each macro-element. The studies based on in-situ surveys after seismic events allowed to create collections (called abaci) of the typical damages occurring in constructive typologies (buildings, churches), which led to a systematization of the mechanical models able to describe their behaviour by kinematic models.

Kinematic models provide a coefficient $c = a/g$ (where a is the ground acceleration and g the gravity acceleration), which represents the seismic masses multiplier characterizing the limit of the equilibrium conditions for the considered element. In simplified assessment procedures, the mechanism connected to the lowest value of c is the weakest one and, consequently, the most probable to occur: in-plane mechanisms are characterized by c coefficients higher than the out-of-plane ones (Borri et al., 1999).

This approach of limit analysis applied to existing masonry buildings in seismic areas is now provided by the updated Italian seismic code (NTC 2008; OPCM 3274/2003, OPCM 3431/2005), which finally takes into account the high vulnerability of existing masonry buildings not satisfying assumptions commonly more suitable for new earthquake-proof structures. In this field, another important document is represented by the Guidelines for the evaluation and mitigation of seismic risk of the architectural heritage (LGBC, 2006).

A PROCEDURE FOR THE VULNERABILTY ASSESSMENT

An automatic procedure for the vulnerability assessment, set up at the University of Padova in the last decade and based on the limit analysis of macro-elements in masonry buildings, has been recently implemented in Visual Basic and updated according to the new requirements of the Italian seismic codes.

Vulnus (Bernardini et al., 1989) is a procedure for global vulnerability assessment of masonry buildings with sufficient regularity (in plane and in elevation) and limited height, both isolated and grouped in complex nuclei of interacting constructions. Processing the data obtained from the survey of selected buildings, the methodology is able to combine different mechanisms, by evaluating the ratio between the critical value of the mean seismic acceleration response, corresponding to the in-plane resistance of the wall systems (*I1* index) and to the out-of-plane mechanisms activation limit of each wall restrained by the floor slabs and transverse walls (*I2* index), and the acceleration of gravity *g*. The local acceleration at the level of the different floors is estimated assuming a distribution proportional to the height. Once the seismic hazard of the zone is known, it is possible to execute preliminary safety assessments of the buildings in seismic conditions, according to codes prescriptions.

Moreover, the two coefficients *I1* and *I2* are combined together with another vulnerability index (*I3*), giving further qualitative information on buildings and soil characteristics: this index is obtained from the data collected by a detailed survey form (G.N.D.T. 2nd level survey form for the vulnerability evaluation of masonry buildings). This is performed through a knowledge based fuzzy vulnerability model (Bernardini, 1999), in order to get a linguistic judgement on the probability of heavy damage of the single building or of a selected group of buildings: five different levels are proposed (probability “0 -very small”, “1 -small”, “2 -average”, “3 -high”, “4 -very high”). In the end, it is possible to get the expected values of heavy damage, through the computation of vulnerability curves for the single building or for a group of buildings, and to compare these results with the curves related to the macroseismic intensity scale EMS98 (Grunthal, 1988): Vulnus in fact permits, through a pattern recognition procedure, to select for each building the EMS98 vulnerability class that better fit with the fragility (probability of exceeding a fixed damage level) of the building.

Figure 15-a clarifies the concept of vulnerability class, according to the EMS98 macroseismic scale: it is possible to see that buildings of the same type (such as masonry buildings) may belong to different vulnerability classes (especially A, B and C vulnerability classes), although in each case a frequent central class is identified. In fact, the belonging of a building or of a group of buildings to a vulnerability class depends on the relative frequency of the levels of damage occurrence (the scale defines six levels from

level 1 negligible damage to level 5 destruction - Figure 1-b), varying the macroseismic intensity degrees (from fifth degree, when damages to the more vulnerable buildings appear, to twelfth degree).
Applications of the procedure on different building typologies are discussed in the following section for the centre of Sulmona.

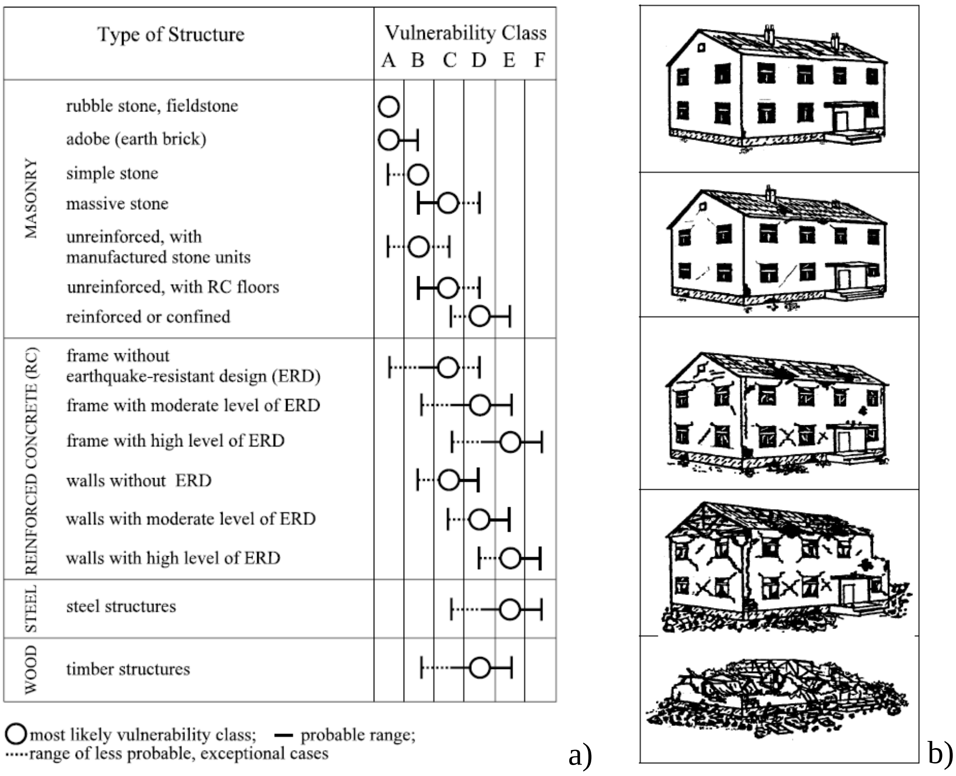


Figure 15:
a) Distribution of building types in the more reliable, possible and exceptional vulnerability classes according with the EMS98 scale;
b) Classification of damage (5 degrees: D1: Negligible; D2: Moderate; D3: Substantial to heavy; D4: Very heavy damage; D5: Destruction) according with the EMS98 scale (Grunthal, 1988).

Seismic hazard and considered buildings

The Appenini mountains, especially in the Abruzzo Region, present a high and widespread seismic activity: among the major seismic events of the past 1349 and 1706 are the most relevant. In fact, the maximum macroseismic intensities historically detected at Sulmona have been 9,5 (1706 earthquake) and 8,5 (1349 earthquake - Stucchi et al., 2007). Using the equation proposed by (Guagenti and Petrini, 1989) it is possible to get the values of a/g (at the site) corresponding to those values of intensity: it is possible to assume $a/g = 0.26$ and $a/g = 0.14$.
The seismic hazard values have been calculated by the National Institute of Geophysics and Volcanology on a grid of points that covers, with steps of 0.02 degrees, the entire national territory, indicating for each point the reference values of the maximum peak ground horizontal acceleration on rigid ground a_g: (Workgroup M.P.S., 2004): considering the codes, fixed the exceedance probability (10% in 50 years - the limit state of preservation of life), the return period (475 years), the foundation ground type (B), the topographic factor ($S_T = 1.0$) and chosen the value for the behaviour factor ($q = 2.25$), for the considered buildings a value of $a/g = 0.31$ is obtained (seismic intensity 10 according to Guagenti and Petrini).
Six aggregates of the historic centre of Sulmona (identified as ISO 27, 39, 48, 69, 87 and 92 - Figure 16) were considered.
As pointed out by the codes for the analysis of aggregate buildings, it is essential to determine the Structural Units (US), identifying the spatial connections, juxtapositions and overlaps and taking into account that these portions of aggregate must have a unitary structural behaviour under static and dynamic loads. Even in the application of the Vulnus methodology, it is necessary to simplify the structural aggregates subdividing them in different structural parts which have uniform height and volume. It is therefore possible to identify 32 units to be analyzed in Sulmona.

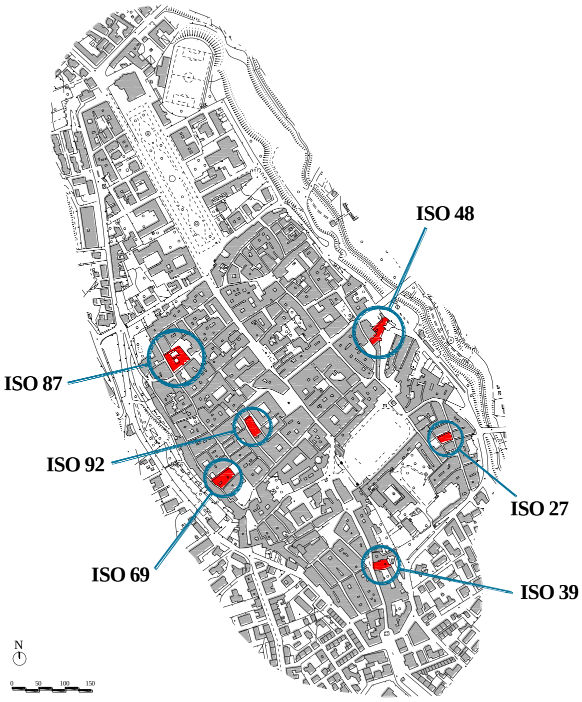


Figure 16: Analysed buildings in the historical centre of Sulmona.

Analysis of the Vulnus results

Regarding the results obtained with Vulnus, according to the analysis of the in-plane and out-of-plane resistance, the index *I1* is higher than *I2* for most of the buildings: this confirms the greater vulnerability of the masonry walls of historical buildings towards out-of-plane mechanisms, rather than towards in-plane damage mechanisms. Moreover, the highest values of the indexes are for buildings belonging to strengthened units, or placed inside the blocks (not in a tip position in the aggregate).

Figure 17 shows a graphical representation obtained from the linguistic vulnerability assessments given by the program for the individual units, in which the aggregates were divided, and for the three reference values of a/g: for a/g = 0,31 the vulnerability of the buildings in Sulmona is, in most cases, Very High, while considering a/g = 0,26 (maximum macroseismic intensity historically detected) the vulnerability is in more than half the units, Average.

In addition to the vulnerability assessment carried out for the individual units in which the aggregates were divided (Vu), the procedure is able to perform an analysis referred to the group of buildings (Vg). According to the linguistic judgement of Vulnus, the vulnerability degree of the entire group of buildings is Very High for a/g = 0,31 and High for a/g = 0,26.

Through the Vulnus methodology it is also possible to assess the vulnerability of the groups of buildings through fragility curves (Figure 18), comparing three curves, in order to estimate the expected value of the frequency of Heavy damage E[Vg] for the different values of PGA/g (central values) and the uncertainty related to this value (the lower and upper limits). Referring to PGA/g = 0.31, it is possible to obtain for Sulmona a value of E[Vg] > 0.9. Considering the historical earthquakes, for PGA/g = 0.26 is E[Vg] = 0.8 and for PGA/g = 0.14 is E[Vg] = 0.4, with a high uncertainty on these values.

Using a pattern recognition procedure it is possible to select for each considered unit the EMS98 vulnerability class that better describes the fragility of the unit. According to this criterion, it results that for Sulmona 1 unit of the sample are classified into A class, 25 units are in B class and 6 in C class.

Figure 19 shows, separately for the 3 homogeneous groups in which the sample can be divided according to the EMS98, the comparisons between the fragility curves related to damage >D2 calculated by Vulnus and the similar values implicit in the EMS98 scale definition, essentially based on statistical information of observed damage due to earthquakes that hit different areas. It is possible to observe a reduction of uncertainty considering rather homogeneous samples.

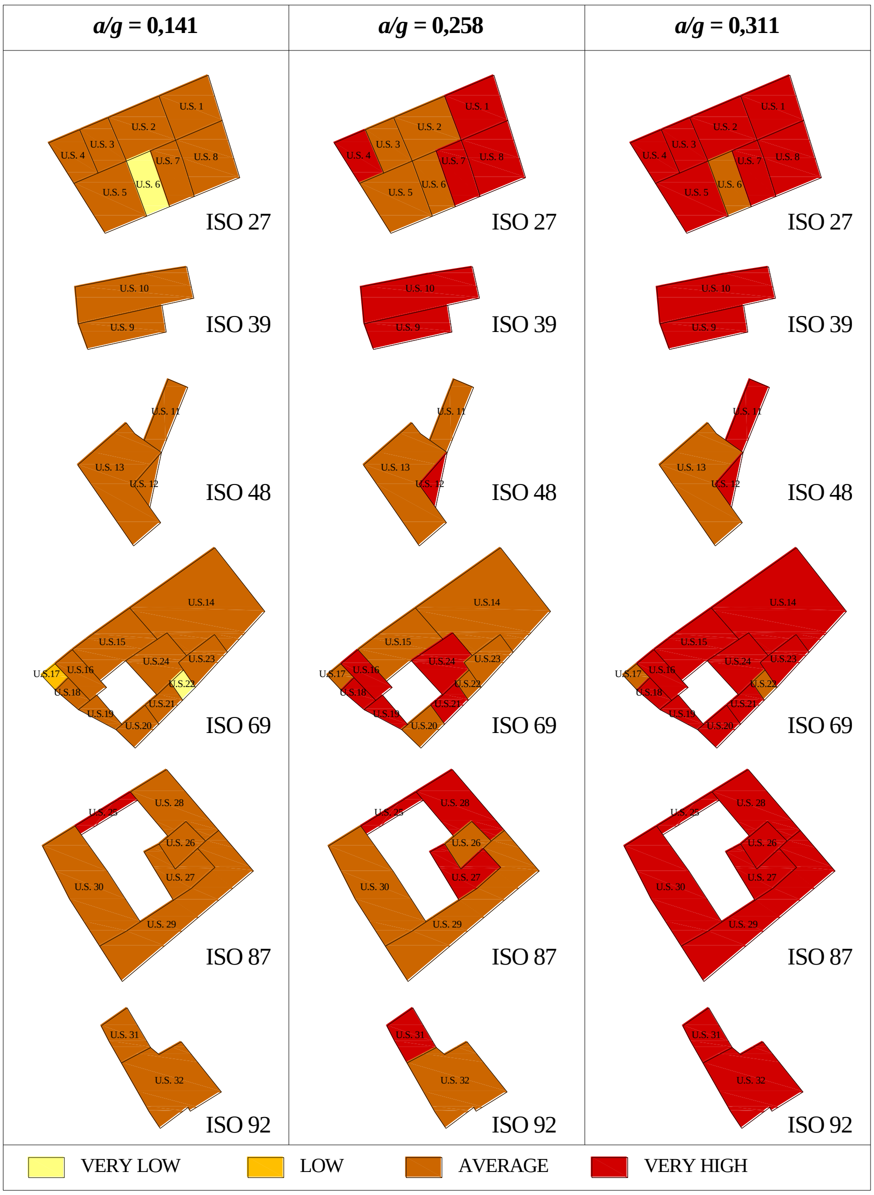


Figure 17: Linguistic vulnerability judgments given by Vulnus for the individual units in Sulmona for different reference values of *a*/*g*.

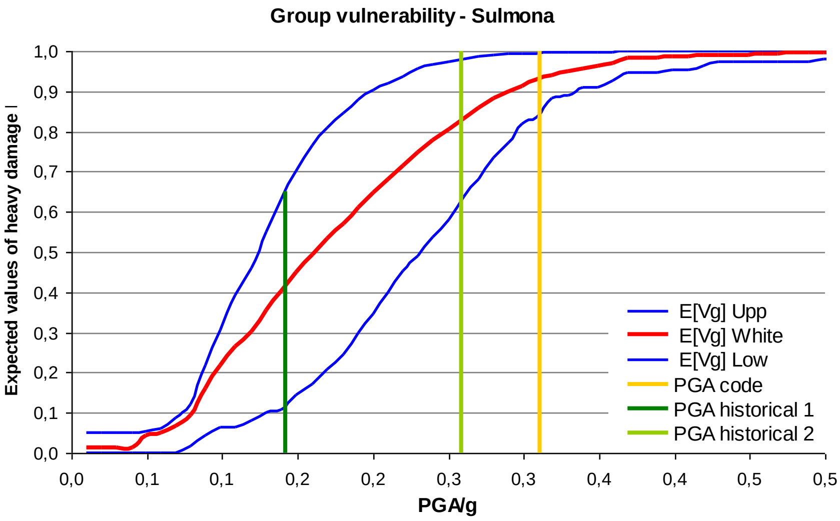


Figure 18: Vulnerability curves obtained with Vulnus for the entire group of aggregates in Sulmona.

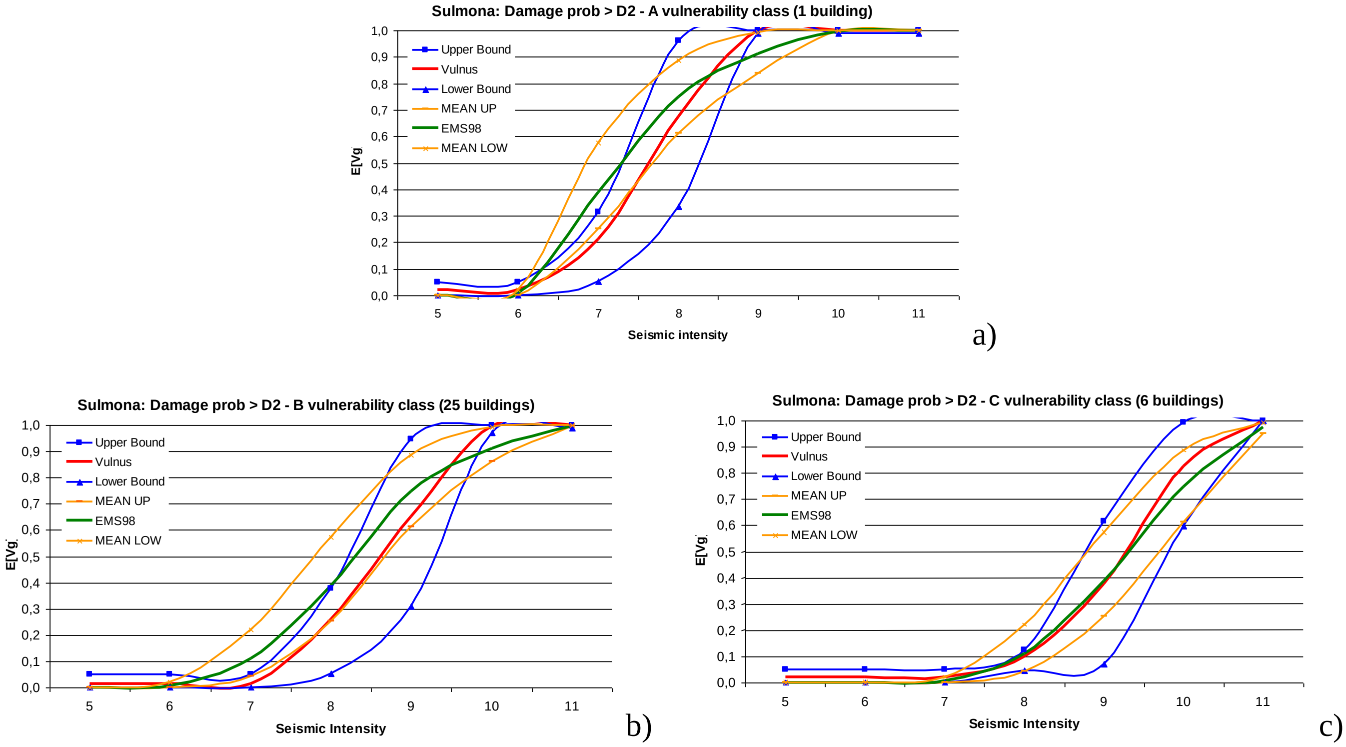


Figure 19: Comparison of the fragility curves for damage >D2 for the homogeneous groups of buildings in a) A, b) B and c) C vulnerability class within the sample of 6 masonry aggregates surveyed in the historical centre of Sulmona (AQ), with the corresponding values implicit in the EMS98 scale definition.

CONCLUSION

The seismic vulnerability assessment of historical buildings should consist of an articulated procedure based on indirect and direct sources of information, leading to the identification of the most typical failure mechanisms activated by the earthquake and allowing for appropriate analytical models. The paper describes the application of a multi-disciplinary procedure, addressed to an articulated knowledge of morphological and constructive aspects of the masonry elements of stone-masonry buildings in the historical centre of Sulmona.

The results have been used for the application of the automatic procedure Vulnus rel. 4.0 (Binda et al., 2007) to obtain a global seismic vulnerability assessment, based on a probabilistic evaluation of the percentage of structural units exceeding a fixed damage level. Despite the approximations made by the developed calculation method, based on the analysis of the collapse mechanisms of structural macro-elements, the results obtained with the Vulnus automatic procedure are reliable, especially for more complex typologies. In fact, as expected, the buildings considered in the historical centre of Sulmona, characterized by different levels of aggregation, show a different vulnerability and safety level. The number of units classified with Vulnus in the B EMS98 vulnerability class is relevant (about 80%): these elements confirm a highly fragile seismic behaviour of very complex aggregates.

According to the experimental results, indicating a low quality of the masonry constituting the analyzed cases study, it turned out that the structural units in the historical centre of Sulmona, if subjected to seismic action, show a better in plane than out of plane response, demonstrating a very high vulnerability.

Other tests were carried out on other palaces in Ovidio street and Peligna streets, but no significant results were obtained.

Nevertheless during the double flat jack tests unexpected displacements distribution (and so tension) was observed in the masonry. Comparing this aspect with the historical one (many heavy seismic events in the same buildings over centuries) teaches us to consider other aspects, such as the intrinsic ductility of that poor masonry. This parameter maybe should also be considered in the vulnerability analysis. More research should be carried out on this masonry typology and mainly on the contribution of the mortar in the general behaviour.

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REFERENCES

- Anzani, A., Baila, A., Penazzi, D., Binda, L. (2004). “Vulnerability study in seismic areas: the role of on-site and archives investigation”, *Proc. of the 4th Int. Seminar on Structural Analysis of Historical Constructions*, Padova, Vol. 2, 1051-1059.
- Anzani, A., Binda, L., Cantini, L. Cardani, G., Saisi, A., Tedeschi, C. (2007). “On site and laboratory investigation to assess material and structural damage on some churches hit by an earthquake”, *Proc. of the 12th Conference ANIDIS - L’ingegneria sismica in Italia*, Pisa.
- Benedetti, D. and Petrini, V. (1984) “A method for evaluating the seismic vulnerability of masonry buildings” *L'Industria delle Costruzioni*.
- Bernardini, A., Gori, R., Modena, C. (1989). *An application of coupled analytical models and experiential knowledge for seismic vulnerability analyses of masonry buildings*, in A. Kortize (ed.), Engineering aspects of earthquake phenomena, Omega Scientific: Oxon.
- Bernardini, A. (1999). *Random and fuzzy sets in the modelling of uncertain engineering Systems*, in I. Elishakoff (ed.), Whys and Hows of uncertainty modelling: Probability, Fuzziness and Anti-Optimization, Springer: Wien, New York.
- Binda, L., Baronio, G., Gambarotta, L., Lagomarsino, S., Modena, C. (1999). “Masonry constructions in seismic areas of central Italy: a multi-level approach to conservation”, *Proc. of the 8th North American Masonry Conference*, Austin, U.S.A., 44-55.
- Binda, L. (2000), *Caratterizzazione delle murature in pietra e mattoni ai fini dell’individuazione di opportune tecniche di riparazione*, C.N.R.-G.N.D.T., Roma, - in Italian.
- Binda, L., Cardani, G., Penazzi, D., Saisi, A. (2003). “Performance of some repair and strengthening techniques applied to historical stone masonries is seismic areas”, *Proc. of the ICPCM a New Era of Building*, Cairo, Egypt, Vol. 2, 1195-1204.
- Binda, L., Cardani, G., Saisi, A., Modena, C., Valluzzi, M.R., Marchetti, L. (2004). “Guidelines for Restoration and Improvement of Historical Centers in Seismic Regions: the Umbria Experience”, *Proc. of the 4th Int. Seminar on Structural Analysis of Historical Constructions*, Padova, Vol. 2, 1061-1068.
- Binda, L., Cardani, G., Saisi, A., Valluzzi, M.R., Munari, M., Modena, C. (2007). “Multilevel Approach to the Vulnerability Analysis of Historic Buildings in Seismic Areas Part 1: Detection of Parameters for Vulnerability Analysis through on Site and laboratory Investigations” and “Part 2: Analytical Interpretation of Mechanisms for Vulnerability Analysis and Structural Improvement”. *Restoration of Buildings and Monuments*. vol. 13 - 6.
- Binda L., Anzani A., Cardani G., Martinelli A., (2009), “Valutazione della vulnerabilità sismica di edifici complessi in muratura: casi di studio nei centri storici di Sulmona (AQ)”. In: XIII Conv. Naz. L’Ingegneria Sismica, ANIDIS. 28/06-02/07/2009, Bologna, 1- 10.
- Borri, A., Avorio, A., Cangi, G. (1999). *Riparazione e consolidamento degli edifici in muratura, in Regione dell’Umbria*, in F. Gurrieri, “Manuale per la riabilitazione e la ricostruzione postsismica degli edifici”, DEI Tipografia del Genio Civile: Roma - in Italian.
- Cardani, G., Anzani, A, Binda, L., Saisi, A. (2008). “On site structural assessment of Churches in Stone work damaged by the Earthquake”, *Proc. of the 2nd Canadian Conference on Effective Design of Structures*, Hamilton, Ontario, Canada.
- Grunthal, G. (1988). *European Macroseismic Scale*, in Cahiers du Centre Européen de Géodynamique et de Séismologie, vol. 15, pages 1-97.

- Guagenti, E. and Petrini, V. (1989). "Il caso delle vecchie costruzioni: verso una nuova legge danni-intensità", *Proc. of the 4th Conference ANIDIS - L'ingegneria sismica in Italia*, Milano, Italy, Vol. I, 145-153 - in Italian.
- Giuffrè, A. and Carocci, C. (1999) *Codice di pratica per la sicurezza e la conservazione del centro storico di Palermo*, Laterza: Bari - in Italian.
- LGBC 2006, Italian Ministry for Cultural Heritage and Activities (2006). "Guidelines for evaluation and mitigation of seismic risk to cultural heritage".
- NTC 2008, Decreto Ministeriale 14/01/2008. "Norme Tecniche per le Costruzioni" - in Italian.
- OPCM 2003, Ordinanza del Presidente del Consiglio dei Ministri n. 3274 (2003). "Primi elementi in materia di criteri generali per la classificazione sismica del territorio nazionale e di normative tecniche per le costruzioni in zona sismica" - in Italian.
- OPCM2005, Ordinanza del Presidente del Consiglio dei Ministri n. 3431 (2005). "Ulteriori modifiche ed integrazioni all'Ordinanza del Presidente del Consiglio dei Ministri n. 3274" - in Italian.
- Penazzi, D., Valluzzi, M.R., Cardani, G., Binda, L., Baronio, G., Modena, C. (2000). "Behavior of historic masonry buildings in seismic areas: lessons learned from the Umbria-Marche earthquake", *Proc. of the 12th IBMaC,* Madrid, Spain.
- Stucchi et al. (2007). "DBMI04, il database delle osservazioni macrosismiche dei terremoti italiani utilizzate per la compilazione del catalogo parametrico CPTI04", http://emidius.mi.ingv.it/DBMI04/, *Quaderni di Geofisica*, Vol 49, page 38 - in Italian.
- Valluzzi, M.R., Michielon, E., Modena, C., Binda, L. (2001). "Modellazione del comportamento di edifici in muratura sotto azioni sismiche: l'esperienza Umbria-Marche", *Proc. of the 10th Conference ANIDIS - L'ingegneria sismica in Italia*, Potenza - in Italian.
- Workgroup M.P.S. (2004). *Redazione della mappa di pericolosità sismica prevista dall'O.P.C.M. 3274 del 20/03/2003 – Rapporto Conclusivo per il Dipartimento della Protezione Civile,* I.N.G.V., Milano - Roma, 65 pp. and 5 appendices, http://esse1.mi.ingv.it/ - in Italian.