Safety assessment of masonry building aggregates in Poggio Picenze, following the L'Aquila 2009 earthquake

E. Spacone, V. Sepe & E. Raka
University "G. D'Annunzio" of Chieti-Pescara, Department of Engineering and Geology, Italy

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SUMMARY
The April 6, 2009 earthquake severely damaged the historical centre of Poggio Picenze, 15 km East of L'Aquila. The paper describes the experience of a research group supporting the municipality in the reconstruction planning, that includes structural engineers, architects, city planners, conservation experts and geologists, with the aim to enhance the seismic safety of the town. The research includes: 1) guidelines for retrofitting/strengthening on masonry buildings; 2) criteria for choosing the structural model, that derives from the definition of buildings aggregates (i.e. independent structural units); 3) the definition of the inter-connections between the town components (buildings, paths, life-lines, etc.), in order to identify a minimum urban structure able to survive after a major earthquake. This paper mainly focuses on the second issue, and reports on the experience of the research group in the definition of the building aggregates, whose implications are crucial both from the structural and the administrative viewpoint.

Keywords: cultural heritage, post-earthquake reconstruction, masonry buildings, building aggregates

1. INTRODUCTION

The town of Poggio Picenze is located in the Abruzzi Apennines, approximately 15 km east of L'Aquila, the region administrative center. Poggio Picenze is at 760 meters above sea level, with about one thousand inhabitants. It is built on a South facing slope overlooking the impressive landscape of the L'Aquila valley, bounded by the Gran Sasso and Monti della Laga National Park to the North and by the Velino-Sirente Regional Park to the South.

On April 6th 2009, 03:32:39 Italian hour, a strong earthquake measuring Mw=6.3 struck the area around L'Aquila, causing strong damage in Poggio Picenze. The peak ground acceleration (PGA) measured near the epicentre was up to 0.6g, while the estimated PGA in Poggio Picenze was about 0.2g on bedrock. Past quake reconnaissance work shows the strongest damage in the NW-SE direction, according to the orientation of the seismogenic structure, i.e. the Paganica fault, with a relevant propagation toward SE and effects corresponding to a magnitude 9 on the MCS scale. For Poggio Picenze, the quake was estimated at 8.5 on the MCS scale. The mainshock severely impacted the historical village centre, where seven casualties occurred, while the surrounding recently constructed belt, consisting mostly of reinforced concrete structures, suffered minor or no damage.

The present paper reports on the activities carried out in Poggio Picenze by a group of researchers of the University "G. D'Annunzio" of Chieti-Pescara aimed at identifying guidelines for the reconstruction and requalification of the town historical centre. Due to the inherent complexity of the task, a strongly interdisciplinary approach is being used, with the contribution of city planners, structural engineers, cultural heritage experts, architects, industrial designers, geologists.

2. DAMAGE SURVEY

After the April 6th 2009 main shock, an extensive campaign of speedy survey took place in order to assess the damage suffered by private and strategic structures. Structures were classified based on the damage level (from A, corresponding to no damage, to E, corresponding to extensive damage or collapse). The results of this survey, carried out by hundreds of volunteers (civil engineers, architects, geologists) coordinated by the Department of Civil Protection (DPC), are reported on the map of Poggio Picenze (figure 1). The red areas clearly show that the village two oldest cores are almost completely non inhabitable and for this reason the old historical center was and still is closed off. Surviving residents are hosted in temporary dwellings (MAP).

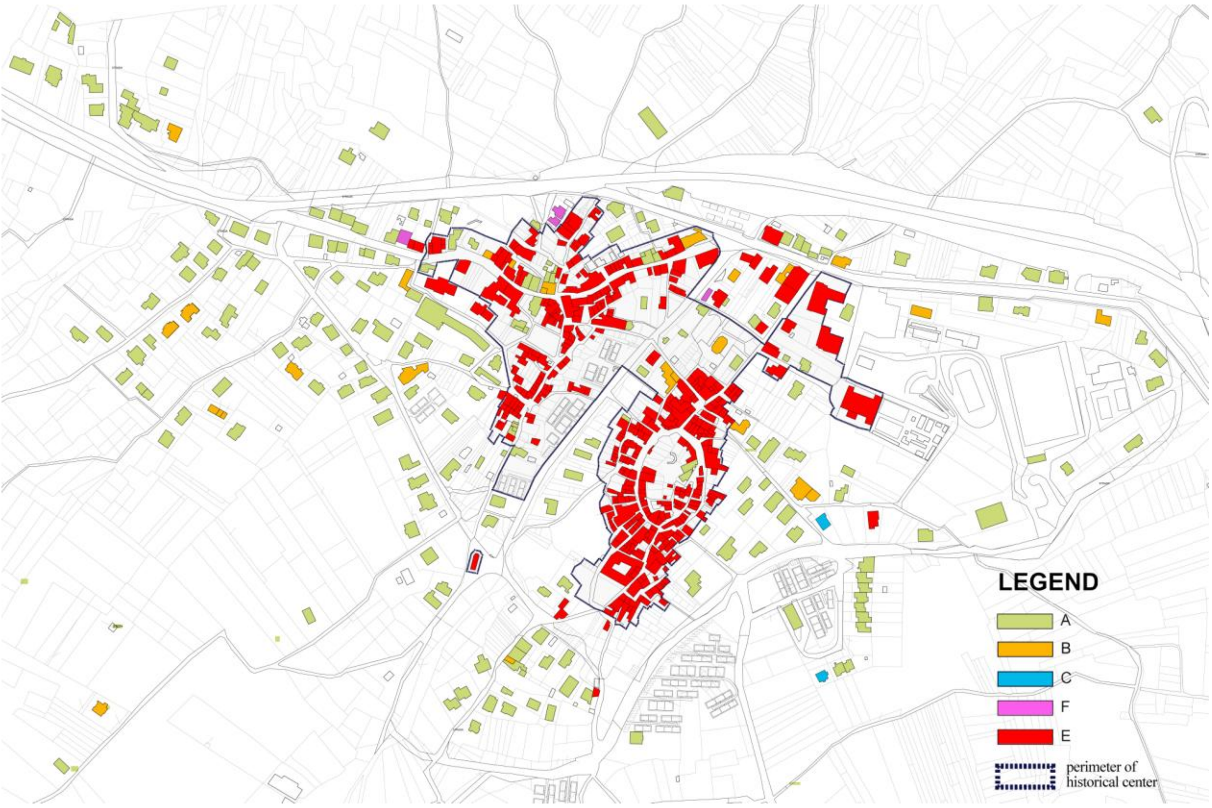

Figure 1. Past-earthquake damage survey in Poggio Picenze; A = no significant damage (inhabitable); B = temporarily non inhabitable, inhabitable with minor/emergency interventions; C = partially non inhabitable; E = non inhabitable (D, meaning " temporarily non inhabitable, requires re-examination", is not significant in the final survey map reported here)

Outside the historical centre there are mostly single, recently built reinforced concrete (RC) buildings, where little or no significant damage was reported. On the other hand, some of the old masonry buildings outside the centre of Poggio Picenze, such as the St. Felice Martire Church, or older RC buildings (such as the elementary school and the kindergarten) suffered significant damage too.

2.1. Characteristics of the built environment and correlation with damage

The historical centre of Poggio Picenze consists of two distinct cores; one develops around the ruins of the so called “castle”, with streets that follow topographic contour lines. The other core develops along the main axis of the ancient Roman Street “Claudia Nova”, with transversal and parallel streets arranged as a sort of comb (figure 2).

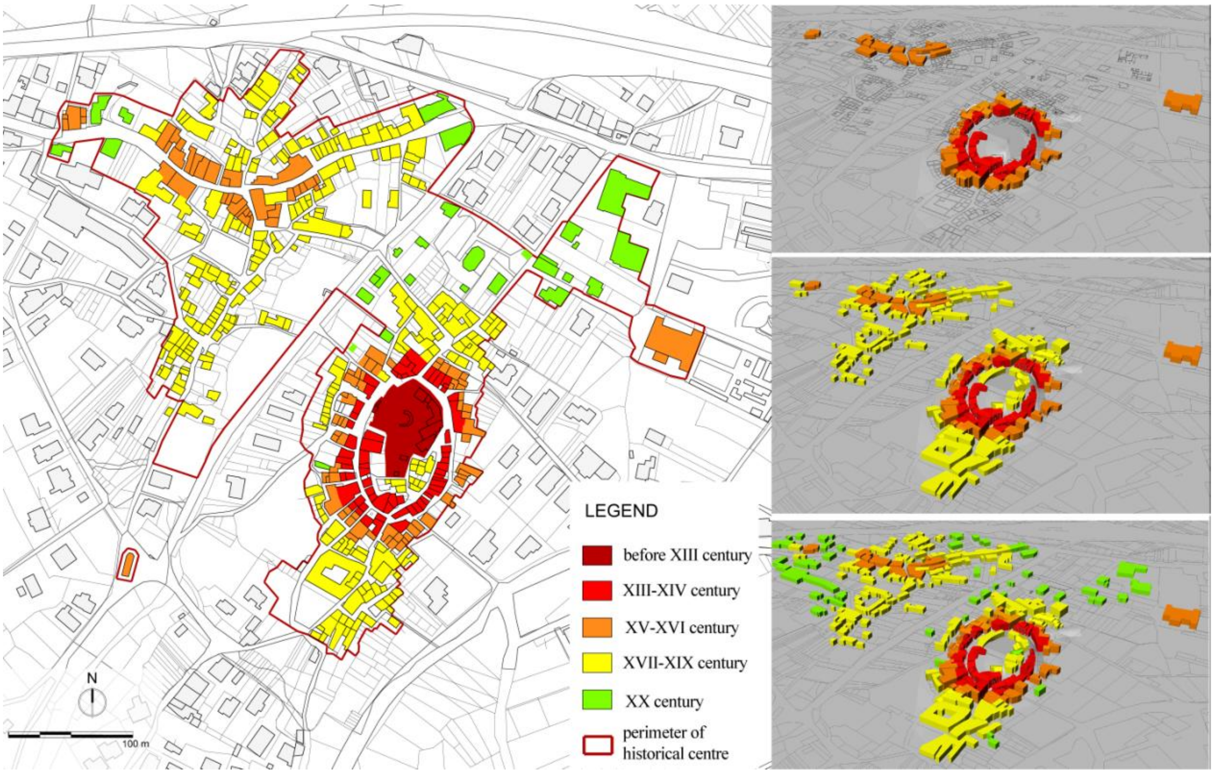

Figure 2. Schematic historical evolution of Poggio Picenze

The main characters of the old town are those of a building (and cultural) heritage that uses basic traditional models. It is for instance easy to recognize buildings that were initially conceived as stables or warehouses for tools or agricultural products, and were then transformed into dwellings. The building criteria and typologies mainly depend on the locally available natural materials, such as stones and wood. These materials are widely found in the historical centre. Straw is also found as filling in some vaults.

Figure 3 shows the comparison between observed damage for the so-called "castle" (a) and several significant building characteristics: age (b), masonry characteristics (c), number of floors (d), roof type (e), strengthening before the 2009 earthquake (f).

As expected, a strong correlation exists between severe damage (Fig. 3.a) and poor quality of the masonry (Fig. 3.c), that characterises the main part of the "castle", while more regular masonry (i.e. roughly squared, with brick layers, or with concrete bricks) exhibits less damage. The older parts of the "castle" (Fig. 3.b) shows higher damage level with several collapses, except for a few buildings that were retrofitted before the 2009 earthquake (Fig. 3.f). However, a strong correlation does not emerge between recent retrofitting (Fig. 3.f) and damage (Fig. 3.a), probably because recent interventions have only dealt with single parts of structural aggregates, while an integrated approach is required (see Sect. 3 below), or some of the work done was mostly architectural. A higher damage level (Fig. 3.a) can also be observed in the case of wooden roofs (Fig. 3.e), particularly when they are old and push on the walls on which they rest. The effectiveness of a newer RC roofs, or new roofs with an RC ring beam, is also highly questionable (Fig. 3.e,f) because of the added mass, as already documented in the scientific literature. No clear correlation can be established between the damage level (Fig. 3.a) and the building height (Fig. 3.d).

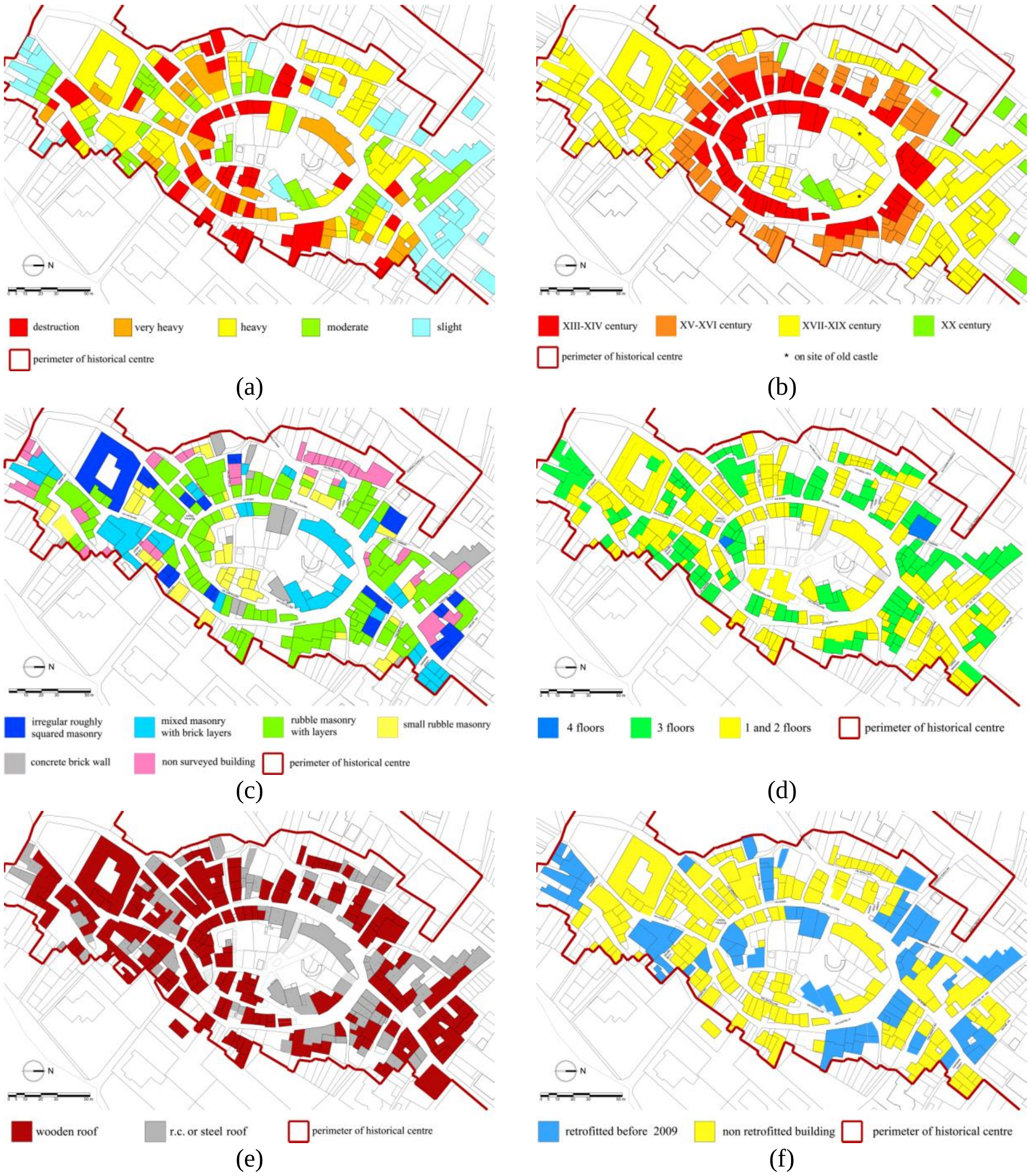

Figure 3. The "castle" of Poggio Picenze: (a) observed damage; (b) buildings' age; (c) masonry characteristics; (d) number of floors; (e) roof type; (f) strengthening before the 2009 earthquake

The study of the traditional building technologies for masonry structures also indicate, in the most seriously damaged buildings, the absence of the box behaviour required for a safe design and imposed in new structures. This derives from the lack of connections between orthogonal walls, between walls and floor slabs or between walls and roof system. Without a box behaviour, the seismic vulnerability mainly depends on the out-of-plane collapse mechanisms of the resisting macroelements – e.g. masonry external walls or portions of them – rather than on the in-plane ultimate strain state in the masonry (e.g. Speranza, 2003).

The structural vulnerability is in such cases evaluated using data mainly related to the geometric configuration of the building macroelements, by means of the so called kinematic approach to the limit analysis of equilibrium. The approach basically consists of analysing all the possible collapse mechanisms of macroelements and then identifying, by means of limit conditions for each mechanism, the smallest multiplier of the reference horizontal forces that activate the out-of-plane mechanisms. Figures 4-5 show some of the collapse (or damage) mechanisms observed in Poggio Picenze.

Figure 4. Corner toppling collapse mechanism

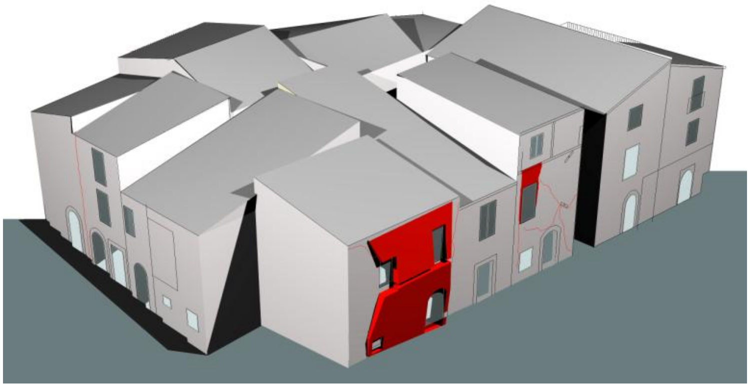

Figure 5.: Wall vertical "bending" collapse mechanism

Degradation and damage scenarios due not only to the seismic event, but also to the lack of maintenance and use were also recorded.

3. BUILDING AGGREGATES

Historical centres (e.g. Giuffré, 1993) are often made of interconnected, multilevel, masonry cells that share common structural elements (walls, roofs, staircases, etc). The structural behaviour (namely, the analysis of the possible collapse modes) must be evaluated considering the entire building aggregate (or simply aggregate, in the following), that can be defined as an assembly of structurally connected dwellings detached or isolated from other structures or aggregates. The sketches in Figures 4-5 show typical situations found in Poggio Picenze.

The definition and delimitation of such aggregates may not be straightforward. Often, buildings in historical centers (not only in Abruzzi) may be linked through "weak" connections, that is connections that have at least one dimension much smaller than those of the structural blocks they connect. Small arches (often added to allow communication between two adjacent buildings), or elements added for seismic strengthening after past earthquakes are examples of such elements. These are elements that would require seismic joints in new structures, but may be present in older buildings where joints are not permitted in order to maintain the culture heritage value of the structure, or cannot be inserted given the structural nature of the element.

Two kinds of questions arise: 1) what is the structural relevance of the "weak" connection? Will it be able to transfer considerable seismic forces to the connected structures during a strong ground motion or will it crash due to its lower size (and strength)?; 2) what is the architectural relevance of the weak connection? Does the element have a cultural heritage significance (or for the town), irrespectively of its structural function? It can also happen that some of these elements, introduced as seismic strengthening devices after previous earthquakes (e.g. a buttress between external walls of two close buildings), are actually ineffective (if not dangerous) according to current experience, although they have to be saved because of their historical value.

One may think that the issue is easily solved by making a larger aggregate that includes the weak connection and the blocks it connects. However, owners and designers (often more than one, or even different designers for each separate apartment) are typically opposed to the solution of a larger aggregate, that forces them to interact and to share all that pertain to the structural safety. While different apartments of a building aggregate are mutually and strongly related from the structural point of view, they may be perceived as independent by the different owners. Finally, some of the apartments are second or third residences, thus are often left empty as the owners live in other parts of Italy or abroad.

On the other hand, the Italian reconstruction guidelines require that different owners in the same aggregate form a consortium, in order to handle all issues of common interest. This requirement is strictly related to the fact that most times reconstruction is paid by public funds (instead of private insurance, basically inexistent in this field in Italy), and therefore building officials need to closely guide and monitor all the reconstruction applications. In this framework, it is fundamental to have a unique interface (or contact person) between the aggregate and the public authorities. Such person is often a project manager (an architect or an engineer) that coordinates the projects proposed by the different owners and their designers.

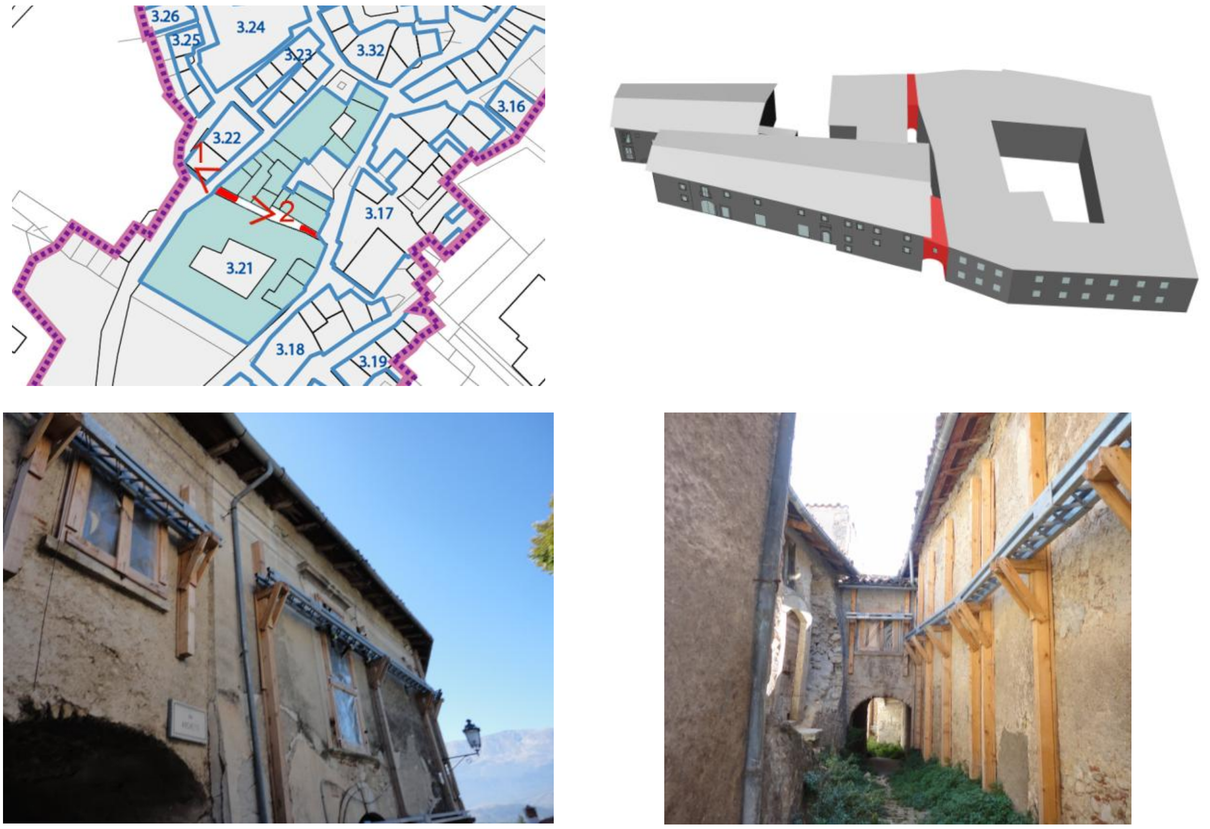

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Figure 6. Example of connection classified as S_1+A_1: structural connection between adjacent buildings through elements (in red) with architectural value from a cultural heritage standpoint

In the above contest, it may be useful to distinguish these “weak” connections in four categories, depending on their architectural and structural functions. If we define S the structural nature of the connection, with subscript 1 indicating an element structurally relevant and 0 a nonstructural one, and if we similarly define with A the architectural (or cultural heritage) significance of the connection, with subscript 1 or 0 indicating the significance or non-significance, respectively, then the following combinations are possible:

a) S_1+A_1 (structural connection through an element with architectural value from a cultural heritage standpoint): Figure 6 shows one such example in Poggio Picenze; in this case it is necessary to save the connection and to consider it in the reconstruction/rehabilitation design process;
b) S_1+A_0 (structural connection with element that does not have architectural value): Figure 7 shows one such example in Poggio Picenze; in this case there is significant freedom, depending on the overall scope of the connecting element; for example, an irrelevant (or even dangerous) connection may be "sacrificed" in a future earthquake, or it may be eliminated in the design stage of the aggregate strengthening;
c) S_0+A_1 (architectural connection with no structural function): Figure 8 shows one such example in Poggio Picenze; this is probably the most difficult case, because the adjacent structures may be considered structurally independent, but forces and displacements transferred through the connection must be evaluated in order to protect its cultural value in the case of a strong ground motion; in this case, the presence of a project supervisor for the two adjacent sub-aggregates should have oversight on the connection;
d) S_0+A_0 (connection element with no architectural or structural significance): in this case the only concern may be the connection destination, but in general there is no constraint for the designer.

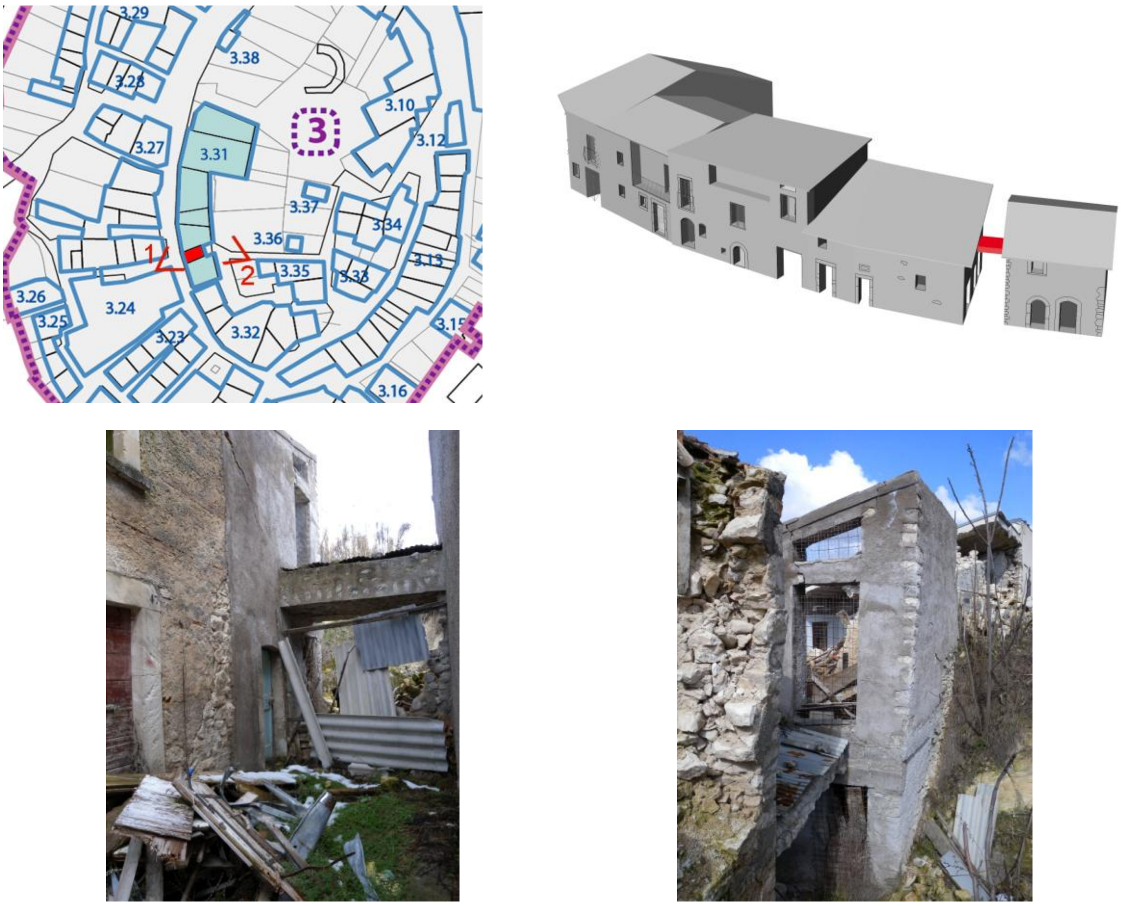

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Figure 7. Example of connection classified as S_1+A_0: structural connection between adjacent buildings through an element (in red) that does not have architectural value

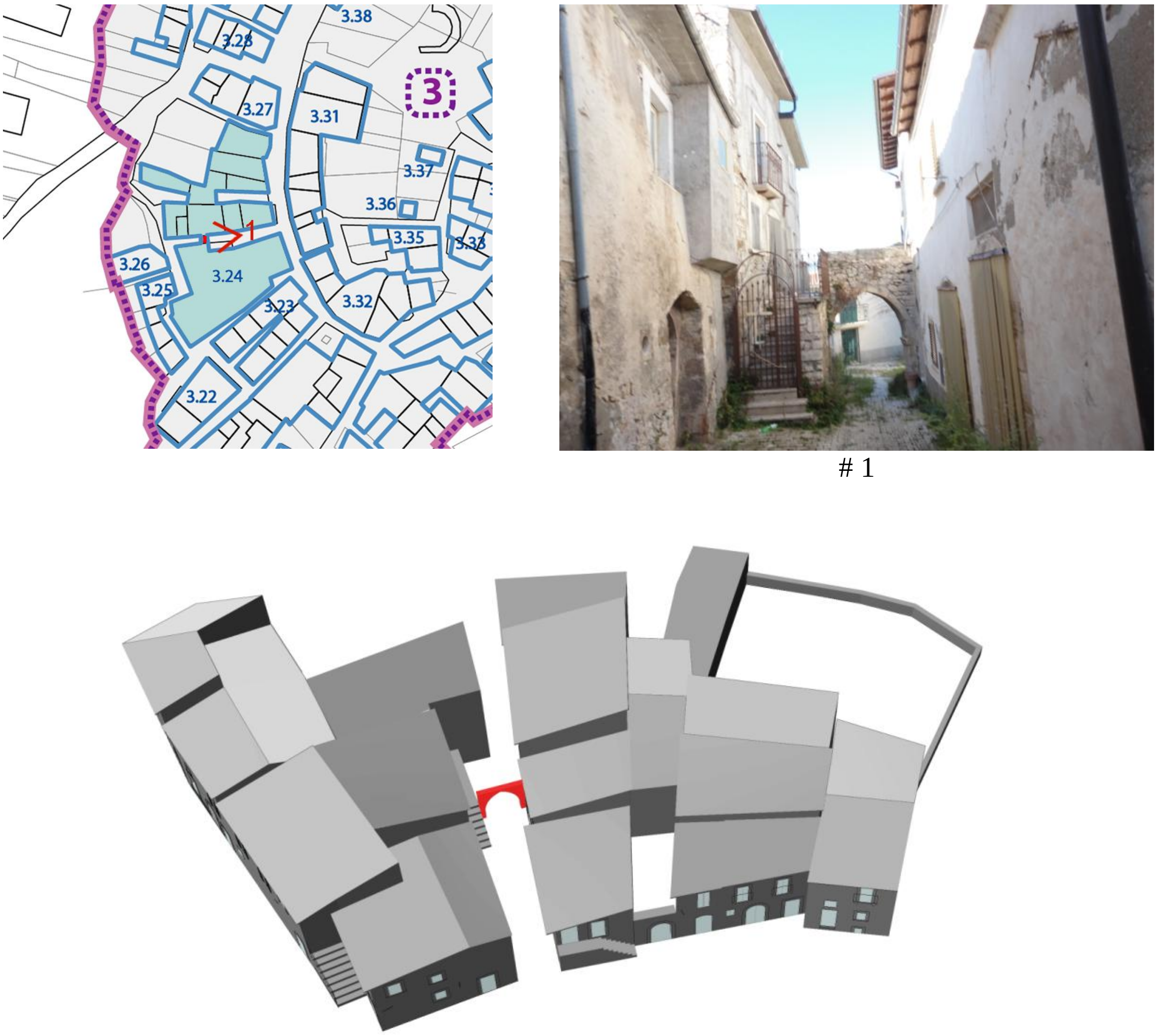

Figure 8. Example of connection classified as S_0+A_1; architectural connection (in red) with no structural function

4. URBAN PLANNING FOR RECONSTRUCTION

Immediately after the earthquake, the local administration and the academic group working with it started planning for future activities (Baldassarri et al., 2010; Sepe et al., 2010). More specifically, the following items are deemed central for the future of Poggio Picenze:

- rebuilding and reopening the old town, with possible changes in building destination (for example from private dwellings to commercial activities);
- giving new life to old traditions and opening of new businesses;
- driving the rebirth of the town as part of a territorial, larger scale plan based on the attractiveness of the surroundings, the current infrastructure, the existing economic activities and the relation between the different small towns and the main urban center, L'Aquila;
- preserve also "minor" or "poor" architecture examples, that is those buildings that may be not classified as significant from a historical viewpoint but contribute to characterize the typical feature of a historical centre;
- grant a higher safety (and efficiency in a post-earthquake scenario) to the old town, viewed as a system of interconnected components.

A related issue is represented by the geology of the site. Preliminary microzonation studies have shown large local amplification factors, and the existence of natural and man-made caves under the city center poses additional challenges to the reconstruction planning.

4.1. Historical center perimeter and building aggregate identification

The first concrete step toward reconstruction was the identification of the damaged historical center perimeter, as required by the reconstruction agency (STM in Italian, Struttura Tecnica di Missione). This perimeter, reported in Figure 2, clearly distinguishes the historical center where special requirements are needed in order to assure a reconstruction process that respects the local building traditions and the pre-existing volumes. In the encircled area, in fact, the reconstruction cannot be performed at the scale of the single building or aggregate; according to recent guidelines for reconstruction by STM, reconstruction must be planned within a systemic approach, that should guarantee a uniform quality and effectiveness of the strengthening and reconstruction actions from a structural, architectonic and town-planning view point. The next step was the identification of the building aggregates, briefly discussed in Sect. 3.

4.2. Minimum Urban Structure

Following other strong, recent earthquakes in Italy, city planners have become aware that the seismic mitigation cannot be guaranteed by exclusively strengthening single buildings. The problem should be tackled at the urban level, because a city is not simply the summation of different buildings, but it works as a network of interconnected elements that include streets, electric power-lines, squares, aggregates, etc. On the other hand, seismic risk can never be completely avoided, and therefore a community, particularly when dealing with an old, historical city center, must agree on the risk level it is willing to accept. An effective policy for reducing seismic vulnerability should therefore consider and compare alternative assumptions of urban planning or urban transformation, without necessarily sticking to a faithful reconstruction of the pre-earthquake urban layout.

The first step is to clearly identify the functions and places or buildings that must be given priority in case of strong earthquakes, such as hospitals, fire stations, town halls, schools, commercial areas and buildings with high occupancy. In a systemic approach, however, roadways and assembly areas, such as squares, must be kept functioning after a major earthquake. Closure of such communication infrastructure does not only hamper emergency access, but it also delays return to a normal urban and social life in older city centers.

Therefore, a urban approach to the reduction and/or control of the seismic risk not only requires the reduction of the seismic vulnerability of the city isolated components, but, most importantly, it requires the identification of the Minimum Urban Structure (abbreviated SUM in Italian) that allows the town to work as a whole: a sort of "smaller" (in the sense of less complex) town into the overall town extension; a sort of basic version of the town system, able to guarantee an acceptable (although reduced) level of interchange between the urban parts, and therefore an acceptable (although reduced) quality of life for the inhabitants.

This concept of Minimum Urban Structure (first introduced by Fabietti, 1999), is one of the main applied research lines for the interdisciplinary group working on Poggio Picenze (Sepe et al., 2011). As explained, the components included in the SUM are not directly related to their low seismic vulnerability, but mainly depend on their role in the urban system, i.e. on the analysis of urban function; quite obviously, this may have a strong impact on the optimal allocation of available resources to reduce the seismic risk.

5. CONCLUDING REMARKS

The work performed by a multidisciplinary group of university experts in support of the reconstruction planning of the historical center of the town of Poggio Picenze, severely damaged following the April 6, 2009 L'Aquila earthquake, has produced a first draft of the guidelines required for the town reconstruction and reopening.

This paper outlines some of the issues that may be peculiar to the reconstruction of old towns, where the inherent cultural heritage value of several buildings (even in the case of minor structures) poses additional constraints to planning, designing, and management for reconstruction.

A high safety level starts from the strengthening of the single building aggregates, that are not always easy to identify due to the presence of "weak", old connections that most times cannot be removed and must be protected against future earthquakes. Multiple-property issues must also be considered in the reconstruction management.

An effective reconstruction must consider safety at the urban level, including planning for escape routes and post-earthquake scenarios in order to guarantee full or partial functioning after future strong earthquakes, in order to avoid partial or full town closing, as was the case after the 2009 earthquake.

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