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Seismic Behaviour and Retrofitting of the Poggio Picenze Historical Centre Damaged by the L'Aquila Earthquake

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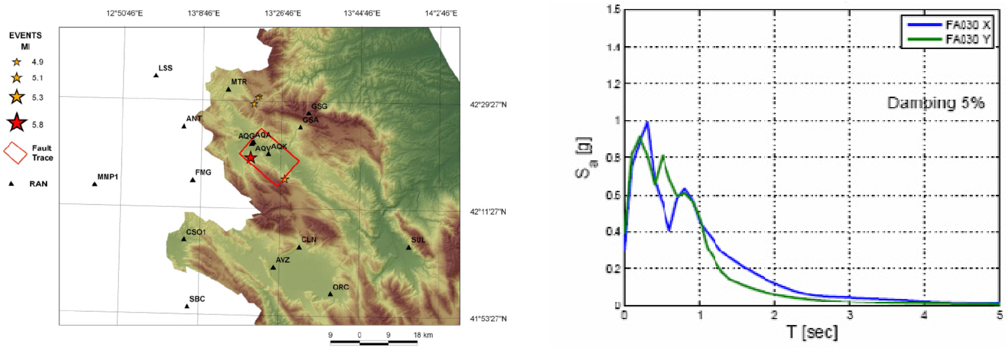
Abstract

Poggio Picenze (Abruzzi region, Italy) was one of the most damaged small towns during L'Aquila earthquake. In particular, its historical centre was strongly hit by this catastrophic event as a result of the different seismic vulnerabilities which have been investigated in this paper. In this framework, after the typological features of the historical centre masonry buildings have been identified and discussed, a case study of a typical building aggregate has been analysed with the purpose of understanding its failure mechanisms when subject to an earthquake. Subsequently, a large scale vulnerability and damage analysis of the examined centre has been performed on the basis of previous study results and the achieved forecasts have been compared with the experimental evidence. Finally, a strengthening method for the investigated masonry walls has been proposed and tested in an experimental way. The experimental results obtained have proved the effectiveness of the implemented reinforcing system to improve the performance of the study walls under seismic actions.

Keywords: historical centres, building aggregates, L'Aquila earthquake, vulnerability analysis, masonry strengthening.

1 The L'Aquila earthquake

On April 6th, 2009 at 3:32 a.m. (1.32 UTC) an earthquake invested the Abruzzo region, a 5000 km^2 area located within the Italian Central Apennines.
The earthquake was generated by a normal fault, located in a valley contained between two parallel mountain along the direction North-South (Fig. 1a) [1], with PGA greater than 0.6g (Fig. 1b), maximum vertical dislocation of 25 cm and hypocentre depth of about 8.8 Km.



a) *b)*

Figure 1. L'Aquila earthquake occurred on 2009 April 6th: identification of the normal fault (a) and elastic spectrum in terms of acceleration at 4.3 km far from the epicentre (b).

The mainshock was rated 5.8 on the Richter Scale (ML) and 6.3 on the Moment Magnitude Scale (MW). Although the epicentre depth was not so deep, the mainshock was followed by many aftershocks, so that the seismic waves associated with shallow quakes produced very long shaking and many damages.

In particular, this earthquake has been defined as an exceptional seismic event because of two reasons:

1) The PGA was larger than the one considered in the new seismic Italian code [2];
2) The area affected by earthquake were very close to the Apennine fault (near-field earthquake).

With reference to the second reason, being L'Aqulla and its districts placed on the fault, the acceleration vertical component, usually not considered in the design phase, produced significant negative effects especially into structures made of material with poor tensile resistance. Moreover, local modes were predominant in comparison to global ones.

Another important aspect to be considered is that the l'Aquila earthquake was also characterised by seismic local amplification effects. In fact, the regional capital of Abruzzo was built on the bed of an ancient lake on the left side of the Aterno river, having a soil structure that amplifies seismic waves. Therefore, the actual geological asset is due to the progressive accumulation of deposit materials (Fig. 2).

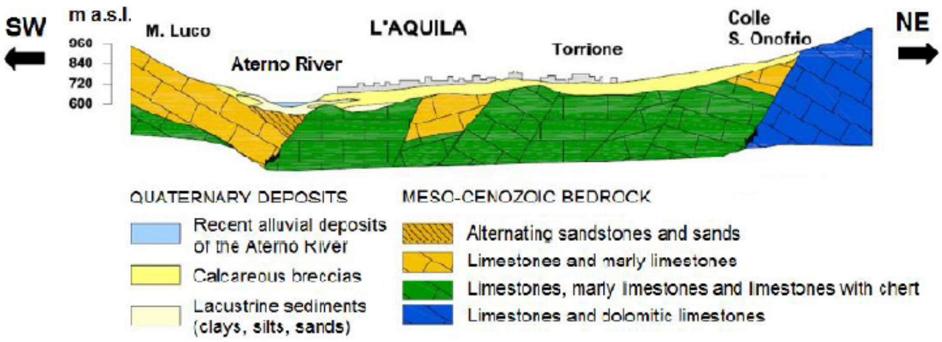


Figure 2. Geologic section corresponding to the centre of L'Aquila.

Coupling near-fault conditions with site effects induced by the complex geological structures further contributes to the complexity of the earthquake ground motion, which has produced very large damages and victims [3].

In particular, this seismic event produced 308 fatalities, more than 1600 injuries, 65000 homeless and severe damages to more than 10.000 buildings in L'Aquila and the surrounding area. Generally, the damaged buildings were part of the historical heritage of the zone, especially churches and palaces with either unreinforced masonry or stone structure.

In the current paper the effect of this exceptional earthquake on the historical centre of Poggio Picenze, a small town in the district of L'Aquila, is investigated.

2 The historical centre of Poggio Picenze

Poggio Picenze is a small town situated on the top of a hill, 760 meters above sea level, and located about 10 km to the South-East of L'Aquila along a slope at the left (north) side of the river Aterno valley. The municipality has a population of about 1000 inhabitants.

The historical centre is the result of the process of continuous urban growth from the ancient times up to the present days. In particular, the farming town can be divided into two different urban areas (Fig. 3).

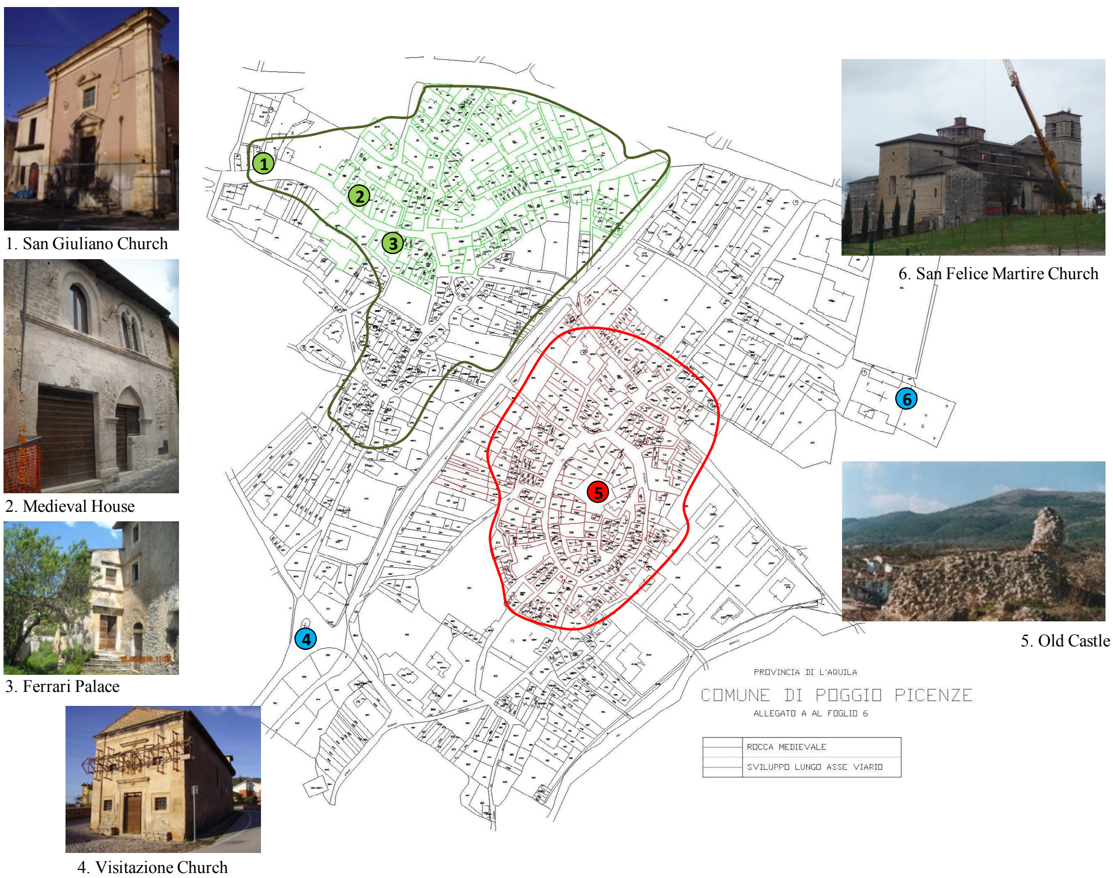


Figure 3. Urban morphology and monumental constructions of Poggio Picenze.

The oldest nucleus was founded by Piceni around the 3rd Century B.C. on the slope of Mount Picenze. The subsequent urban configuration developed around the medieval castle built approximately in the 1st Century A.C. Originally, the ancient castle had fortified walls and six towers, including a high one in the middle. Therefore, in the oldest part, the urban planning is typical of a medieval town with buildings arranged in almost concentric arrays which follow the contours (red area in Fig. 3).

On the contrary, the other area (green area in Fig. 3), which is the new one, has an irregular urban plan with some important palaces, like the mercantile Medieval House, built in the 13th Century.

The entire town suffered heavy damages during the 1762 October 6th earthquake, which required substantial reconstruction works. In fact, the castle of Poggio Picenze became unsafe and it was demolished. Ruins of this structure are still visible in the oldest part of the town.

The most important monumental buildings of the town are the three churches, namely San Felice Martire, Visitazione and St. Giuliano. and two palaces, namely Galeota and Ferrari.

More information on the history and the most important buildings of Poggio Picenze are reported in [4].

Nowadays, thanks to its oldest urban area oriented towards L'Aquila, Poggio Picenze has a privileged position with respect to near towns because of the efficient road system which connect it with San Gregorio and Barisciano from one side and with both the Gran Sasso mountain and the Puglia Italian region form another side.

3 Typological features and seismic response of masonry aggregates

Nowadays, the historical centre consists of masonry complex, generally ranging from 2 to 3 stories. Masonry walls generally have constant thickness along the building height, it varying between 50 and 70 cm. The inter-storey height is about 3-4 m for the first levels and 3-3.50 m for other floors.

Sack stone masonry with chaotic texture inside and bad quality mortar is the typical structure for load-bearing walls, which are, in some cases, connected to each other by metal ties. However, the aggregates are characterised by regular ashlar walls, built with squared stone blocks cut to sizes which correspond to a set number of brickwork courses. In larger buildings, the sack constructive practice was detected where the walls are made of two external layers of cut stones with the gap filled with small dimension rubble pieces. Furthermore, cut stone coins are often present in the buildings corners.

About the horizontal structures, masonry vaulted ceilings largely covered the lower storey of the buildings, spanning along one or two directions. Other floor types with flexible diaphragms are made of steel beams and vaulted or flat tiles. Instead, roofing structures are often composed of double frame timber beams with clay tile covering (Fig. 4).

Figure 4. Main structural features of masonry aggregates of Poggio Picenze.

Moreover, from the architectural viewpoint, finishing, doorways, balconies, patios and porches are usually embellished with local limestone, the so-called white stone of Poggio Picenze, which has a gentle appearance and is easy to work (Fig. 5).

Figure 5. Architectural cornices made of the so-called white stone of Poggio Picenze.

Most of the centre of Poggio Picenze was partially destroyed by the L'Aquila earthquake, which produced significant damages to buildings and caused the death of 5 people.

In particular, within the land of Poggio Picenze, three primary seismic vulnerabilities have been detected:

1) the ground response;

2) structural alteration and maintenance, with particular attention to roof changing in terms of both geometrical scheme and materials;
3) masonry apparatus.

In this paper the last two vulnerabilities have been considered and discussed.

With reference to the second seismic vulnerability source, it was noticed that after earthquake some constructions often failed due to either lack in maintenance of roofs or change of the coverage layers. In particular, information deriving from the knowledge of the original roof configuration showed that timber ties are generally hooked up by anchors to top panels outside (Fig. 6).

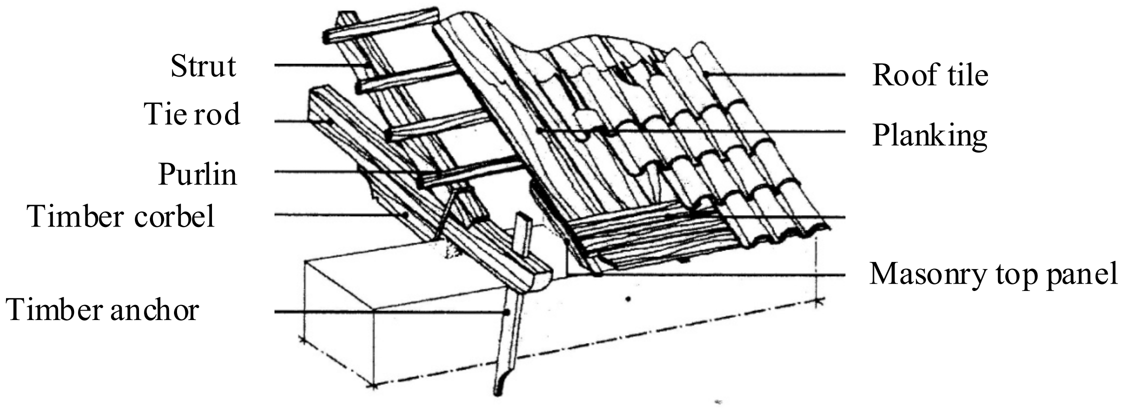


Figure 6. L'Aquila old buildings: a typical roof typology scheme [5].

This valuable roof scheme was often replaced by dissimilar coverings, no effective during earthquake. As a consequence, four different roof conditions were noticed within the investigated small town, they being classified into the following four categories:

A) Original roof scheme with no maintenance operations. Loosing of the original static capacity.
B) Roof structural configuration change. Materials and pitches slope are similar to the existing ones but different engineering details (absence of anchors) are noticed.
C) Roof alteration with material variation.
D) Roof pitch slope changing or roof scheme totally divergent from the original one.

Instead, the third seismic vulnerability source is represented by the masonry apparatus quality, which is directly related to the collapse mechanism derived from alteration of the original roof scheme (category D).

Within the area of Poggio Picenze the main masonry typology is based on small size stones with no transversal section links, no stretcher elements, no bricks layers and no sufficient wedges elements (see Fig. 7).

Therefore, due to the above lacks, a failure of the wall external layers occurs because of buckling phenomena.

(a) *(b)*

Figure 7. A masonry panel detected in the Poggio Picenze area and a 1m x 1m masonry sample (b).

During in situ investigations of several masonry buildings, important failure patterns into both vertical and horizontal structures have been detected. In particular, the following main collapse mechanisms have been identified (Figs. 8 and 9):

- global in-plane mechanisms, consisting of storey shear failures due to diagonal shear cracks in the masonry piers; local crushing of the masonry with or without expulsion of material;
- global out-of-plane mechanisms, characterised by either whole or partial wall overturning or walls bending collapse, generally triggered by vertical cracks at the wall corners; rocking;
- other global mechanisms, such as irregularity among adjacent structures and floor and roof beam unthreading, due to permanent deformation of either tie-beams or their anchorages; vertical cracks along the interface between two adjacent buildings.
- local mechanisms, especially consisting of lintel or masonry arch failure, local weakness, corner overturning in the upper building part caused by diagonal and vertical cracks within the masonry spandrels or cracks in the keystone arches.

(a) *(b)* *(c)*

Figure 8. Main global collapse mechanisms: (a) in-plane, shear failures due to diagonal shear cracks in the masonry piers; (b) out-of-plane overturning; (c) diagonal wedge and horizontal bending.

(a) *(b)* *(c)*

Figure 9. Main local mechanisms: (a) lintel failure; (b) collapse of the masonry external layer; (c) vertical cracks in masonry piers.

4 Local scale analysis: the seismic behaviour of a masonry building aggregate

The found damage map due to seismic actions allows to individuate in a precise way the crack development and the typical lacks of hillside aggregates.

Within this masonry building typology, a typical aggregate placed on a subsoil susceptible to undergo amplification of seismic waves, increased by the presence of natural hollows, has been investigated.

The building aggregate is developed linearly along the hillside with an elongated configuration of the block (Fig. 10) [6].

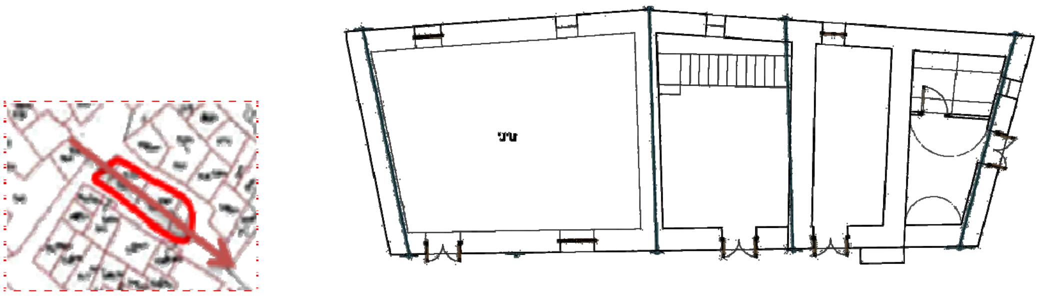


Figure 10. Block configuration and plan layout of the studied aggregate.

Masonry walls have thickness variable from 50 to 70 cm and the inter-story height changes from 3.00 to 4.50 m. Windows, often not aligned each other, are within the range [10-30%] of the masonry wall volume and are located at the right distance with respect to the wall intersections.

The aggregate building showing major damages is the head one, placed in a leading position at the maximum level. In fact, for this structural unit, three of the four external walls are exposed to seismic action effects and, therefore, it is more vulnerable than other aggregate buildings. Such buildings, other than represent useful restraints for the other construction volumes, if provided with appropriate seismic devices, can represent an anti-seismic *unicum* of closed masonry boxes.

However, if we look at the damage pattern of one of longitudinal facades of the aggregate after earthquake (Fig. 11), it is found that the whole block has not played the role of structurally continue system. In fact, the not rational interventions developed in the past years finalized to the building modernization have led, together with the lack of roof-top masonry panel connections, to the devastating mechanism of the observed façade damage.

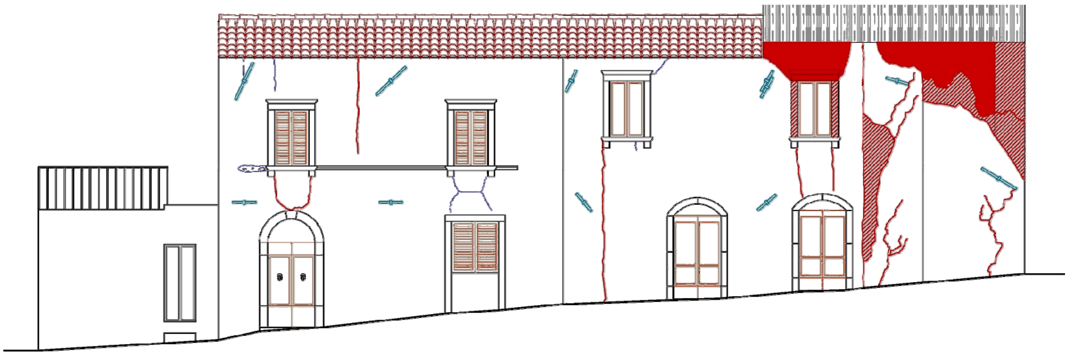


Figure 11. Post-earthquake damage survey of a longitudinal facade of the study aggregate.

On the other hand, the facade on the right of the longitudinal facade above examined is damaged with second mode local failure mechanisms (Fig. 12). Shear cracks show as the façade left part is rotated into anti-clock way, with detachment of a panel portion producing a vertical crack propagated up to the opposite panel side, and a relative slip among arch key elements is occurred.

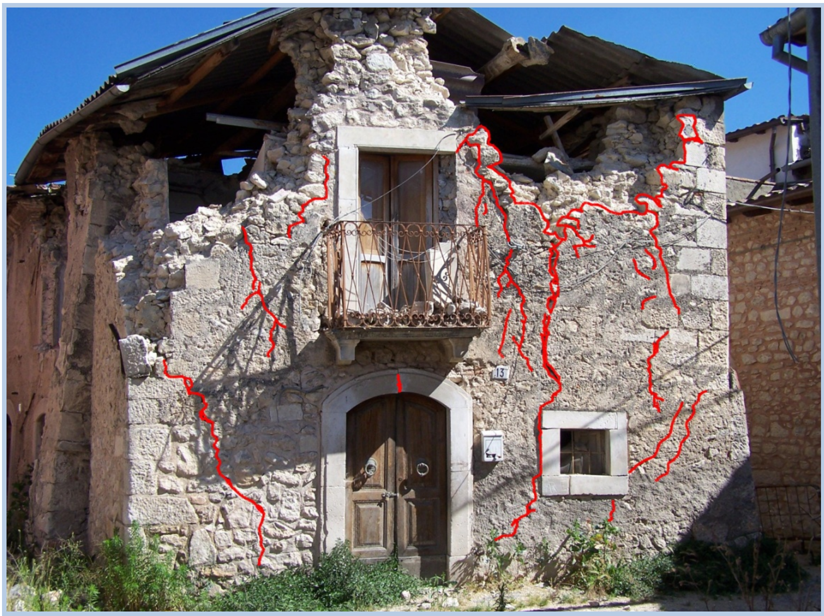


Figure 12. Post-earthquake damage survey of the transversal facade of the study aggregate.

In addition, the above described mechanism involves part of the angle panel in common with the longitudinal facade before investigated. Thanks to both the good connection between orthogonal walls and the presence of a steel tie-beam, only the top part of the masonry angle is failed.

On the right side of the transversal facade, due to two arches located orthogonally to the same facade (Fig. 13), two sub-vertical cracks are developed. So, the resulting masonry panel confined by these two vertical cracks, not having a monolithic behaviour, does not allow the formation of some mechanism type, but shows the collapse of its external masonry layer.

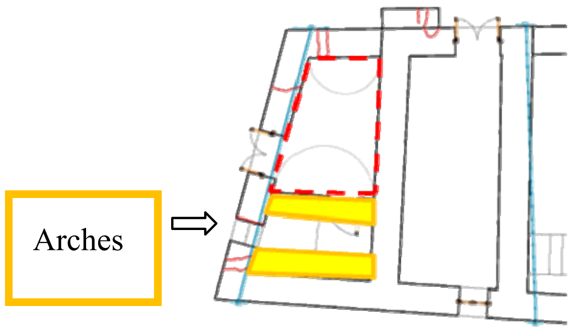


Figure 13. Post-earthquake damage of the transversal facade of the study aggregate due to the presence of arches orthogonal to the facade.

This is produced by the incapacity of the masonry wall, composed of irregular masonry stones without transversal connections within its thickness, to exhibits out-of-plane overturning due to the premature material disaggregation, which inhibits the development of the rotational plastic hinge necessary to the mechanism activation.

Such a collapse mechanism has been very diffused within the entire municipality of Poggio Picenze and, in general, in all small towns in the district of L'Aquila.

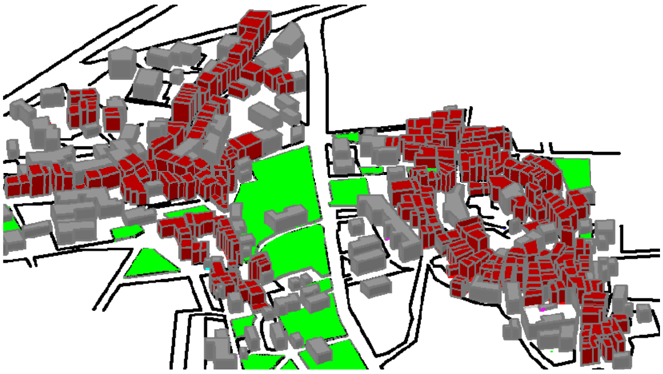
5 Seismic vulnerability and damage assessment on a large scale

The large scale seismic vulnerability analysis of the historical centre of Poggio Picenze has been performed by means of the simplified procedure already applied to the town of Torre del Greco in the framework of the COST C26 Action "Urban Habitat Constructions under Catastrophic Events" [7].

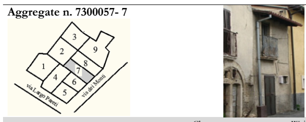
The work is aimed at the extension of the quick approach calibrated on the built-up of the Campania Region to geographical zones recently affected by earthquake, where the feasibility of the proposed large scale analysis method of aggregates can be proved by the direct comparison between foreseen damages and real ones.

Therefore, the method has been applied to 51 masonry aggregates of building, composed of 284 structurally independent units (Fig. 14). For each building, the vulnerability index has been computed by filling the survey form explained in [8] and reported in the same Figure 14.

Afterwards, a seismic damage analysis has been carried out by evaluating the mean damage grade according to the results reported in [9]. This procedure has permitted to estimate the aggregate damage level, comparing it to the effectively suffered one, related to a seismic intensity equal to the L'Aquila earthquake one.



Aggregate n. 7300057- 7



Parameter	Classes A	B	C	D	Weights K	Scores V
1. Organization of vertical structures	0	5	20	45	1	3,72
2. Nature of vertical structures	0	5	25	45	0,25	1,16
3. Location of the building and type of foundation	0	5	25	45	0,75	3,49
4. Distribution of plan resisting elements	0	5	25	45	1,5	1,39
5. Plain regularity	0	5	25	45	0,5	4,18
6. Vertical regularity	0	5	25	45	1	0,00
7. Type of floor	0	5	25	45	1	4,65
8. Roofing	0	15	25	45	0,5	2,32
9. Details	0	0	25	45	0,25	0,00
10. Physical conditions	0	5	25	45	1	0,93
11. Presence of adjacent buildings with different height	-20	0	15	45	1	0,00
12. Position of the building in the aggregate	-45	-25	-15	0	1,5	-12,55
13. Number of staggered floors	0	15	25	45	0,5	4,18
14. Effect of either structural or typological heterogeneity among adjacent structural units	-15	-10	0	45	1,2	-2,23
15. Percentage difference of opening areas among adjacent facades	-20	0	25	45	1	-3,72
Vulnerability Index						**7,52**

(a) *(b)*

Figure 14. Seismic vulnerability assessment of the historic centre of Poggio Picenze: the examined aggregates (a) and a typical form filled for a given aggregate structural unit (b).

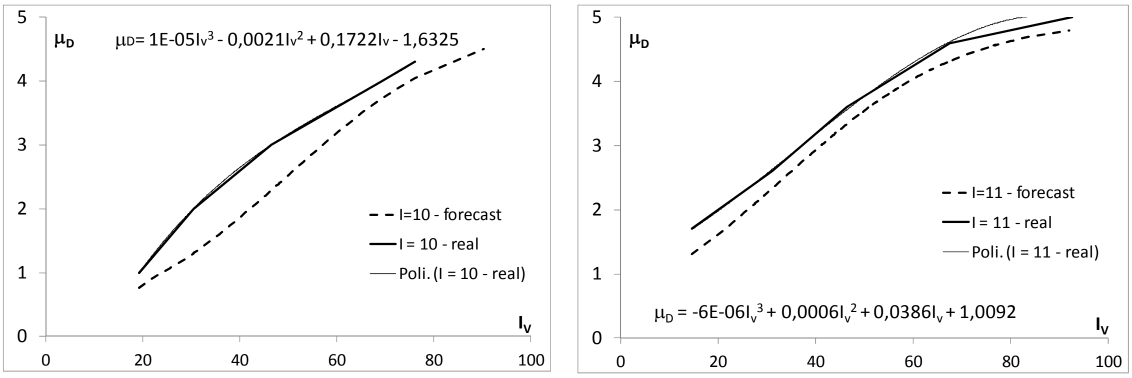
In particular, since seismic registrations have revealed that, depending on the ground nature of the site, the seismic intensity range detected in Poggio Picenze was between VII and IX grade of the MCS scale, different values of seismic intensity have been considered. In fact, the western side of the town is settled on a coarse-grained Pleistocene formation, whereas most of the historical centre is founded over the carbonate silt formation of San Nicandro, locally covered by layers of the Pleistocene gravel. This latter formation outcrops even at the toe of the hill [10].

The post-seismic damage of masonry aggregates has been estimated on the basis of their external visual inspection by assigning to each structural unit a mean damage μ_D grade ranging between 0 and 5 according to the EMS 98 scale [11]:

- light damages: $0 < \mu_D \leq 1$;
- moderate damages: $1 < \mu_D \leq 2$;
- heavy damages: $2 < \mu_D \leq 3$;
- very heavy damage: $3 < \mu_D \leq 4$;
- failure: $4 < \mu_D \leq 5$;

From visual survey it was noticed that in the castle zone, the old buildings were heavily damaged, whereas minor damages were detected in the western and downhill parts of the town, where the foundation soil is based on the coarse-grained Pleistocene formation.

So, based on the damages detected in the old centre of Poggio Picenze, numerical relationships between the mean damage and seismic vulnerability and macroseismic intensity have been achieved. In particular, considering the two macroseismic intensity levels detected in the centre (I = 10 and 11), third-order polynomial equations between the average damage degree and the expected level of vulnerability, have been derived (Fig. 15).



(a) *(b)*

Figure 15. Comparison between the expected mean damage grade and the occurred one within the building aggregates of Poggio Picenze: the west zone (a) and the castle area (b).

The curves derived from really detected damages have been then compared with those obtained by applying the empirical formulation found in [9] by using the vulnerability index calculated according to the form proposed in [7] and appropriately converted in the range [-0.02÷1.02] [8].

The comparison between the real damages and the estimated ones which took place in two areas of the old town of Poggio Picenze is illustrated graphically in Figure 16.

(a)

Figure 16. Comparison between forecast damages (a) and real ones (b) (continues).

Figure 16. Comparison between forecast damages (a) and real ones (b).

The comparison shows that the proposed procedure does not provide a conservative estimate of the building aggregate behaviour under earthquake. This result could be produced from coupling near-fault conditions with site effects induced by the complex geological structures, which further contributes to increase the complexity of the earthquake ground motion effects.

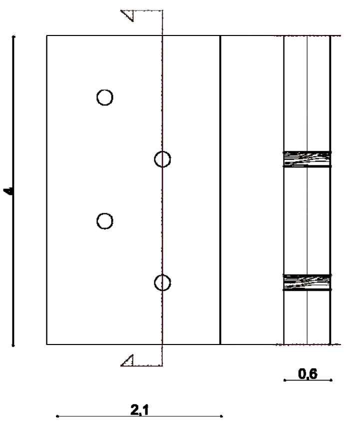
The analysis of additional Abruzzo historic centres affected by the 2009 earthquake, as well as the careful evaluation of site effects, represent the future developments of the study which will have as its ultimate goal the definition of a seismic damage - vulnerability law taking into account the actual seismic hazard of the investigation site.

6 A masonry wall reinforcing technique

The analyses performed in the historical centre of Poggio Picenze have shown the high seismic vulnerability of masonry walls due to two principal lacks, that is absence of transversal connection elements (headers) and no contact among stones. These deficiencies must be eliminated in order to guarantee a better seismic behaviour of the study masonry walls. Nevertheless, the better strengthening approach is really difficult to be selected. In order to define an effective and sustainable strategy of intervention, strictly connected to this masonry typology, a destructive in-situ experimental campaign on full-scale structural walls belonging to an existing building was planned, it being conducted from the University of Naples "Federico II" in collaboration with the University of Reggio Calabria (coordinator Michele Candela), the University of Perugia (coordinator Antonio Borri) and the University of Genova (coordinator Sergio Lagomarsino) [12, 13, 14, 15]. This experimental research project was developed also with the collaboration of the Municipality of L'Aquila. The test campaign was directed both to the identification of L'Aquila masonry panel mechanical parameters and to the behavioural assessment of panels under both dynamic and static conditions.

Among the proposed consolidation techniques, considering that the study masonry did not respect the so-called "rules of art" for masonry panels, the University of Naples designed a traditional reinforcement strategy based on both placement of timber headers within the masonry thickness and replacement of mortar joints with wedge elements.

In particular, some timber headers were placed within the panel thickness in order to obtain the mechanical interlocks of the two panel layers. To this purpose, the masonry set-up reading was important since the difference between the two panel faces allowed to define a unusual headers setting scheme, which is schematically illustrated in Figure 17a. The executive phases of the strengthening method foresaw the panel drilling with 4 circular holes (diameter of 200 mm) along the whole panel thickness, the setting of wooden headers with the regular stress condition re-established by wooden wedge elements and the replacement of mortar joints with stone wedge elements (Fig. 17b and c).



(a)


(b)


(c)

Figure 17. Placement scheme of timber headers within masonry panel (a), executive phases (b) and detail of both timber header and stone wedge elements (c).

The panel, having width of 2.10 m, height of 4.00 m and depth of 0.60 m, was before cyclically tested by means of a hydraulic jack under "displacement-control", with the possibility to produce displacements in alternate directions, and then pulled out with the same jack in the final test phase. The pushing action of the jack, placed at a height of 2.25 m, was applied to the panel through a rigid box steel beam anchored to it by steel bars. The test set-up was arranged to take advantage of panel position in the building scheme (Fig. 18).

Figure 18. Details of the test set-up.

The data resulting from experimental test, referred to the hydraulic jack position, are reported in Table 1, where it is apparent that the maximum obtained force F_{max}, corresponding to a displacement of 0.22 m, is 1469 daN. In the table the pushing force is the load applied to the panel at the jack level, whereas M_o is the overturning bending moment and M_s is the stabilizing bending moment. The achieved results were then compared to other results obtained from experimental tests on different panels (without reinforcement, reinforced with concrete headers, reinforced with injections), which presented both dissimilar geometrical dimensions and disparate jack application height. To this purpose, the maximum forces, and therefore the pushing actions, attained by each panel was homogenised each other with reference to a 1.00 m large masonry portion (see Fig. 19).

F_{max} (daN)	F_{homol} (daN)	Pushing force (daN)	M_o (daN*m)	M_s (daN*m)	Efficiency compared to a rigid block response (M_o/M_s)
1469	1653	787	1574	1570	**1**

Table 1. Strengthened panel response compared to the rigid block behaviour.

By comparing the behaviour of the panel without reinforcement (Table 2) with the one strengthened by means of timber headers, it is possible to notice that performed intervention produces improvement in masonry mechanical interlock which, together with the wedge elements influence, allows to attain a total force four times more than the one of the original panel (see Fig. 19). In particular, the presence of stone wedge elements produce a strength increase two times than the one of the panel reinforced with concrete headers only.

F_{max} (daN)	$F_{homol.}$ (daN)	Pushing force (daN)	M_o (daN*m)	M_s (daN*m)	Efficiency compared to a rigid block response (M_o/M_s)
176	277	166	290	1373	**0.21**

Table 2. Unreinforced panel response compared to the rigid block behaviour.

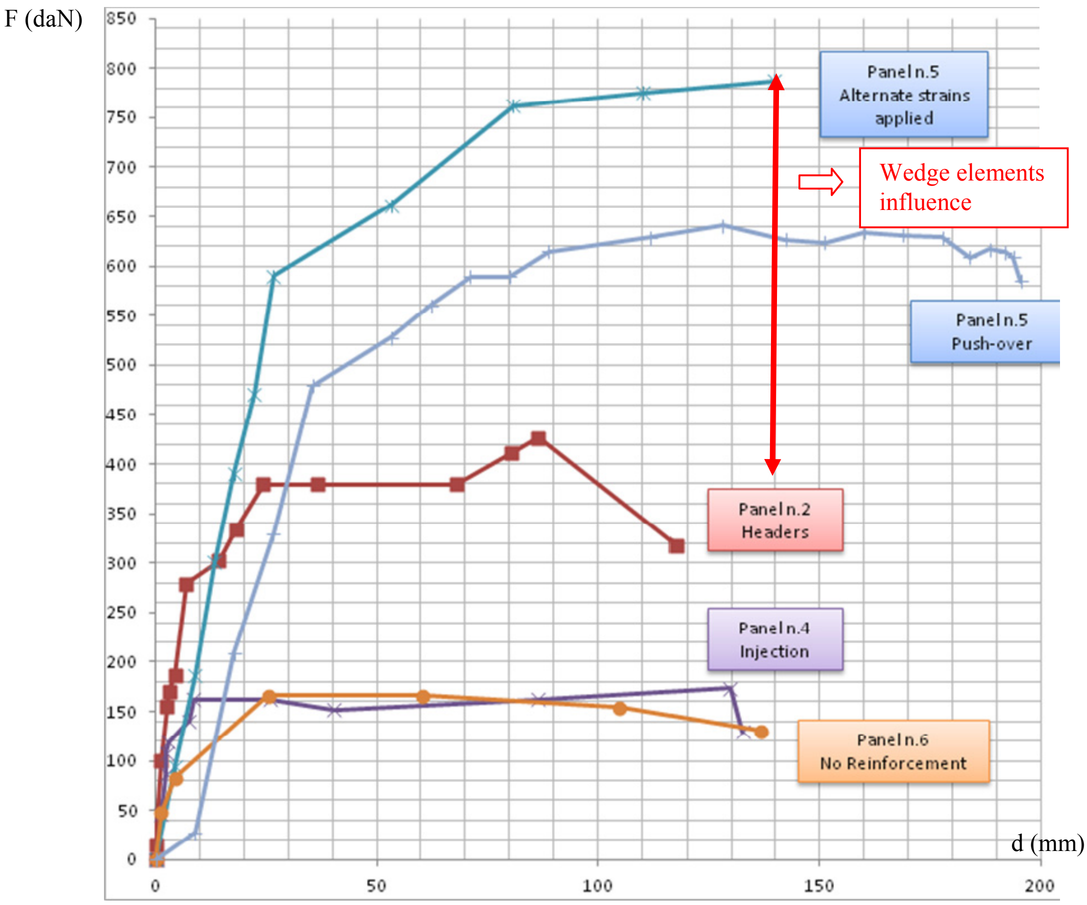


Figure 19. Comparison among strengthened masonry panels.

The results of the presented experimental activity have demonstrated the effectiveness of the proposed consolidation technique, which can be usefully applied for strengthening L'Aquila building masonry.

7 Conclusions

In the current paper the seismic behaviour of the historical centre of Poggio Picenze (L'Aquila, Italy) has been investigated and discussed in detail by performing both comprehensive and large scale in-situ surveys.

During these survey activities, two main seismic vulnerabilities were detected: maintenance lack and structural alteration of roofs in terms of geometrical scheme and materials and both absence of transversal connection elements (headers) and no contact among stones into masonry walls.

Both of these seismic deficiencies were detected into a typical hillside building aggregate analysed as a case study, they producing both in-plane and out-of-plane collapse mechanisms. In particular, the absence of roof-top masonry wall connections produced the overturning of masonry panel portions, whereas the lack of headers within the masonry thickness provoked the disaggregation of the external layer of the masonry wall, which was not able to exhibit a monolithic behaviour.
Subsequently, a new seismic vulnerability and damage assessment procedure on large scale was applied to the investigated historical centre.

The achieved results in terms of damage were compared with really detected damages. In this case, a third degree polynomial relationship between vulnerability index and mean damage grade was derived for each of the two different historic centre zones, namely west area and the castle zone, characterised by different seismic intensity.

The comparison among results showed that the proposed procedure does not provide an estimation on the safe side of the seismic behaviour of building aggregates. This result could be produced from coupling near-fault conditions with site effects induced by the complex geological structures of Poggio Picenze, which further contributes to increase the complexity of the earthquake ground motion effects on built-up.

The analysis of additional Abruzzo historic centres affected by the 2009 earthquake, as well as the careful evaluation of site effects, represent the future developments of the study which will have as its ultimate goal the definition of a seismic damage - vulnerability law taking into account the actual seismic hazard of the investigation site.

Finally, since the local and large scale analyses performed showed the very bad seismic performance of the masonry walls studied, a strengthening strategy has been implemented for them, it being based on the use of both connections among masonry layers and stone wedge elements. These interventions are used to guarantee both vertical and horizontal mechanical interlocks of masonry according to the "rules of art", which are not generally fulfilled in the Abruzzo constructive practice for masonry walls.

Therefore, an experimental test on a masonry panel strengthened with the above interventions, namely headers plus stone wedge elements, was carried out. The achieved results showed a substantial seismic performance increase of the tested reinforced panel, able to both behave as a rigid block and attain a strength level four times larger than the unreinforced panel one.

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