Study of vulnerability and damage: the case study of Castelnuovo after L'Aquila earthquake (Italy)



B. Ortolani, A. Borghini, S. Boschi, E. Del Monte & A. Vignoli Department of Civil and Environmental Engineering, University of Florence, Italy

SUMMARY

After the L'Aquila earthquake (04/06/2009), the authors surveyed the building stock of Castelnuovo, a hamlet in the San Pio delle Camere Municipality (L'Aquila). The macroseismic effects reached intensity 9.5 (MCS scale) at Castelnuovo. The shaking caused collapse of 50% of the whole built that includes 102 aggregates and 324 structural units.

First of all a brief description of the methodology (with reference to EMS-98 classification) used in the surveys are presented. Then, the main results of the study, in terms of structural typologies and analysis of vulnerability and damage, are defined. By means of the analysis of vulnerability and the geology characteristics of soil, an evaluation of the damage is proposed.

Finally in the paper local seismic responses of masonry building aggregates are evaluated: the main results in terms of qualitative classification of out-of-plane mechanisms for the panels are discussed.

Keywords: L'Aquila earthquake, EMS-98, vulnerability, damage, aggregates

1. INTRODUCTION

The seismic sequence that struck the province of L'Aquila began in December 2008. The main shock was recorded at 03:32 a.m. of 04/06/2009 (epicenter coordinates N 42.342 and E 13.380, Fig.1.1.), with macroseismic intensity varying between 8.0 and 9.0 of the MCS scale, equivalent to local magnitude M_L 5.8 and moment magnitude 6.3 M_W .

Already in the past that area was interested by earthquakes with effects above the damage threshold.

The strongest historical earthquakes in the catalogue CPTI04 (Working Group CPTI, 2004) are those of the September 9, 1349 (M_W 6.5) and February 2, 1703 (M_W 6.7). The shock of 04/06/2009 is not comparable to these seismic events, which are related to energy releases much higher. However, a comparison can be done with other earthquakes that have affected the area. The earthquakes of 1461 (M_W 6.5), 1762 (M_W 5.9), 1916 (M_W 5.2) and 1958 (M_W 5.2) in particular.

In this paper the activities carried out by the authors in the period of 2009-2011 in Castelnuovo are described.

Castelnuovo (Fig.1.2.a.) is a hamlet in San Pio delle Camere Municipality (L'Aquila), situated at about 20 km east of L'Aquila.

The macroseismic effects reached intensity 9.5 (MCS scale) at Castelnuovo and, in fact, the shake caused collapse of the 50% of the buildings (Fig.1.2.b.), serious damage into most buildings and even the death of 5 people.

The village is insert within the complex defense and sighting medieval system, located in the L'Aquila's valley. The whole subsoil of Castelnuovo is characterized by the presence of subterranean tunnels dug into silt (Fig.1.2.c.). Access to tunnels generally corresponds to the ground floor of the buildings directly from the street level. Originally, in fact, ground levels of the building were stables for animals or agricultural storages.

The morphology of tunnels is variable in terms of length, section, number of levels and presence or absence of fill.



Figure 1.1. Territorial framework and individuation of main shock epicenter



Figure 1.2. (a) Aerial photo of Castelnuovo before L'Aquila earthquake. (b) Aerial photo of Castelnuovo after L'Aquila earthquake. (c) Example of subterranean tunnel

2. PROCEDURE ANALISYS ON URBAN SCALE

The activity carried out by the authors mainly consists in the survey of the built and of the collapse mechanisms of the structures. This work has been extended to the entire village, including 102 aggregate buildings, composed by 324 structural units in total.

This activity was aimed to evaluate the seismic vulnerability and damage level, in order to make a comparison with the seismic microzonation made by the Department of Civil Protection DPC (Working Group MS–AQ, 2010).

In particular, the work has been made in two consequent steps (first step 2009-2010, second step 2010-2011); these steps are characterized by different level of accuracy of the in-situ surveys (Borghini et al., 2011).

In the first step (2009-2010), a preliminary screening of the building stock has been performed, collecting all the necessary information to correlate the seismic vulnerability (referring to the presumed conservation status of the buildings before the earthquake) with the level of damage caused by the seismic event of 04/06/2009 and with the seismic microzonation mentioned above. The purpose of the analysis was to investigate all the aspects that may have caused high damage level, looking to the influences of seismic vulnerability and local amplification effects connected to the site characteristics in particular.

In the second step (2010-2011), a detailed survey of all the buildings has been done, carefully investigating all the information already collected in terms of geometry, structural typologies and collapse mechanisms.

2.1. Relevance area

All the analysis explained above have been made on a specific relevance area, limited by the perimeter of the historical city center (Fig. 2.1.), according to the "Decreto del Commissario Delegato per la Ricostruzione della Regione Abruzzo n. 3" of 03/09/2010. Inside this area two different zones have been highlighted because of their historical-architectural value, their uniform constructive features and their level of damage: the area of "Castello" located on the top of the hill and the area situated at the basis of the hill, realized in a subsequent period.

In order to give completeness to the work, the analysis has been extended also to the rest of the village (the area outside the perimeter). The aim is that to have an element of comparison with more recent constructions and which have a better conservation status.



Figure 2.1. Limits of the perimeter

The area inside the perimeter has an extension of about 6.25 hectares; in this zone 70 aggregates have been identified, composed of 285 structural units in total. These buildings correspond to the 88% of the entire building heritage of Castelnuovo.

2.2. Aggregate and structural units

First of all, before introducing the methodology used by the author for the surveys, it is necessary to identify aggregate and the structural units (Fig. 2.2.). An aggregate is a group of structural units, not necessarily homogeneous, interacting each other by links more or less effective. Generally in historical center the aggregate coincides with the urban block.

The structural units are defined as those portions of buildings with structural continuity from top to the bottom, characterized by a common manufacturing process, or by vertical and horizontal homogeneous typological elements that contribute to the uniform distribution of vertical and horizontal loads.



Figure 2.2. Example of an aggregate and structural units individuation

2.3. Survey operations

The surveys have been conducted according to the following procedure:

- critical reading of "Schede di Agibilità AeDES (GNDT, 2000);

- individuation of the aggregates;

- for each structural units these information have been indicated: data, geometric parameters, presence of subterranean tunnels, type of vertical and horizontal structures, construction details, conservation status and occupation one, failure mechanisms, class of vulnerability and damage level in accordance with the EMS-98;

- survey of the masonry panels and sections;

- in-situ tests on mortar with Drilling Resistance Measurement System (DRMS), (Del Monte and Vignoli, 2008);

- samples of mortar and stone elements for laboratory tests.

2.4. Vulnerability and damage

For the study of seismic vulnerability and damage European Macroseismic Scale (Grünthal, 1998) has been adopted, called below EMS-98. That Scal has been chosen not only because it results the most recent scale and probably the one will be used in the future in Europe, but also because of the quality and details with which it describes construction types and damage levels (Giovinazzi and Lagomarsino, 2001).

The EMS-98 defines 6 vulnerability classes (A, B, C, D, E and F representatives decreasing vulnerability) in which different types of buildings but characterized by similar seismic behaviour are grouped.

Damage, instead, is defined by 5 levels (identified by the initials D1, D2, D3, D4 and D5 representatives increasing damage levels) in addition to the situation of absence of damage (D0). Each level is described in detail; also illustrative pictures are included in description. For all types of structures (c.a. or masonry)structural elements damage and secondary elements damage are combined.

3. ANALISYS RESULTS

3.1. Historical evolution

The first Castelnuovo settlement dates back to the Medieval times and it's located on the top of the hill, even called "Castello". The built is characterized by house-walls, where ground and underground floors houses in the external perimeter are vaults, usually used as stables for animals or agricultural storages generally not communicating with the upper floors.

Connective tissue has regular conformation: built distribution follows a perpendicular grid with equal repeated dimension in isolates in which type cell measures about 7x5 meters.

Between nineteenth and twentieth century, village shows marked growth on South-West direction following contour lines. From mid-nineteenth century onward new buildings are inserted in free places existing in urban tissue or among the road which connects San Giovanni street (highway inside the perimeter) at SS17.

3.2. Built characteristics

Buildings within the perimeter are characterized for 52.3% by three floors (two floors and an underground floor), while buildings consisting of four floors are 12.3% which are mainly located among San Giovanni and XXIV Maggio Streets and built about in the nineteenth century's expansion. The remaining part consists of one floor (9.1%) and two floors (26.3%). The average height of interplane is about 2.70 meters.

From the statistical analysis of data collected emerges that type cell is characterized by vertical structure in stone load-bearing masonry (86.3%), generally unorganized with two faces and low quality mortar. There are no transversal links in this type of masonry.

Other construction technologies, as RC frames, walls unreinforced concrete or masonry blocks in particular are principally present in peripheral areas of the village (Fig. 3.1.a.).

Generally, the horizontal elements (Fig. 3.1.b.) of the first floor consist of masonry vaults; at the second floor steel slabs are present (56.7%) (I-beams and hollow tiles, I-beams and hollow building tiles with or without concrete slab and I-beams and reinforced concrete slab), while the roofs consist in wooden beams (80.2%) generally not thrusting in vertical elements.



Figure 3.1. (a) Principal vertical type of buildings. (b) Principal horizontal type at first floor

3.3. Occupation status and conservation status of buildings

For each structural unit occupation status before earthquake has been evaluated by assigning an occupation level among the four below: occupied (1), partially occupied (2), abandoned (3) or under construction/renovation (4). As emerges from the histogram on Fig. 3.2.a. a significant portion of buildings, approximately one quarter of all building stock, was not occupied before the date of earthquake, mainly because of large migrations that have characterized that region in the first years of twentieth century.

It has been also evaluated conservation status of buildings pre-earthquake (Fig. 3.2.b.). Specifically, each structural unit has been classified using one of the following items: excellent (1), good (2), bad (3), severe (4), widespread collapse (5). Buildings inside the perimeter had bad conservation status before earthquake related to the absence of occupation.



Figure 3.2. (a) Occupation status ante-earthquake. (b) Conservation status ante-earthquake

4. VULNERABILITY AND DAMAGE

The detailed surveys made on the building heritage have allowed the assignment of the vulnerability class for each structural units (Fig. 4.1.a.) with reference to the EMS-98 scale.

For the buildings located inside the perimeter of Castelnuovo, about 93% of the structural units lies in the most vulnerable classes (class A and B); in particular, 55.1% of the buildings belongs to vulnerability class A (irregular stone masonry with low efficient connections) and the remaining

38.2% of the buildings belongs to the vulnerability class B (irregular stone masonry with efficient connections or regular masonry with low efficient connections).



Figure 4.1. (a) Vulnerability classes. (b) Damage levels

Also the level of damage (Fig. 4.1.b.) has been evaluated with the EMS-98 scale: for the buildings located inside the perimeter it is possible to observe that 60.4% of the structural units has suffered serious damages to the structural elements (D4 and D5 level of damage), with some cases characterized by total collapses.

In particular, only 15.5% of the units has not suffered damages to the structural elements (D0 and D1 level) while 76.5% is characterized by considerable damages to structural parts (D3, D4 and D5). It is important to underline that the concentration of serious damages (D4 and D5) is mainly located on the top and central part of the village, where the older buildings were.

The extensive in-situ survey of aggregates allowed to systematize the possible activated mechanisms of collapse in a reference abacus. Out-of-plane mechanisms are typical of buildings subjected to horizontal actions orthogonal to their plane with lacking connections between floors and walls and among perpendicular walls.



Figure 4.2. Out-of-plane mechanisms: (a) Overturning of a facade and collapse of the roof. (b) Corner collapse and crumbling of panel. (c) Collapse of all panels. (d) Shear failure in the plane of panel

In the following, a description of the principal out-of-plane mechanisms is given; it is possible to distinguish between: overturning of a monolithic wall (O), overturning of a monolithic wall with corner (OC), vertical bending (overturning of a wall restrained at the top by a tie, VB), horizontal bending (arch effect in the thickness of the façade of wall, HB), corner collapse (CO) and total collapse of panel (C) (Valluzzi et al., 2004).

The percentages of out-of-plane mechanisms are shown in the first histogram above (Fig. 4.4.a.) for stone masonry structural units with high damage level (D3, D4 or D5): the majority of activated mechanisms is classified as overturning of a monolithic wall (36.1%) and it concerns both principal and rear façade of buildings. An high percentage is referred to collapse of walls (54.0%) and it is linked to the structural units with D5 assigned damage level. For each type of local mechanism the number of floors involved is identified. It is significant to report only the result for overturning mechanism because of the large involved data (Fig. 4.4.b.). 30.1% of cases is referred to a single floor

mechanism, 47.9% refers to a two floors mechanism and only 21.9% is referred to an entire wall (three floors).



Figure 4.3. Photos of "Castello" after earthquake: high damage level compared to other areas of Castelnuovo



Figure 4.4. (a) Out-of-plane mechanism. (b) Floors involved in overturning mechanism

4.1. Correlation between the data

Analyzing the correlation between vulnerability and damage levels (Fig. 4.5.a.), as expected, emerges that the most vulnerable buildings also have higher level of damage. In particular, 76.4% of the buildings in vulnerability class A has suffered significant structural damage (D4 or D5 class). The second histogram (Fig. 4.5.b.) shown that the buildings with a very bad conservation status ante

earthquake (53%) have suffered relevant damage (D4 or D5) in 88% of cases, while the buildings for best-preserved this percentage drops to the 66%.



Figure 4.5. (a) Correlation vulnerability-damage. (b) Correlation conservation status-damage

In the context of stone disorganized masonry buildings, which are 86.3% of the buildings inside the perimeter, level of damage and influence of subterranean tunnels have been assessed. For this type of

construction damage levels is significantly higher than for the generally buildings analyses before. In particular:

- 68% of units has suffered significant structural damage (D4 and D5) compared to 60.4%;

- about 8% of the units has not suffered structural damage (D0 and D1) compared to 15.5%;

- about 85% of the units had suffered obvious damage compared to the 76.5%;

It is also necessary to underline that in some cases a primary role was done by the collapse of the calotte of subterranean tunnels. In fact for stone masonry buildings the 79% of cases had D4 or D5 damage level, respect to the 61% related to the built within the perimeter.

Observing at the map of Castelnuovo (Fig. 2.1.) it's possible to make a classification between the buildings inside the perimeter distinguishing by aggregation type. There are, indeed, isolated buildings (14.4%) consisting of single or double structural units, usually coinciding with an estate unit, row buildings (67.4%) that usually have the main prospect facing into street and complex aggregates (18.2%) consisting in irregular shapes generally staggered in accordance with the territory.

Within the stone masonry constructions 87.8% are non-insulated buildings, respectively, 70.7% row aggregates and 17.1% complex aggregates (Fig. 4.6.). The structural units in the aggregates can have corner position, external position or internal one. For stone masonry aggregates analyzed 6.9% are angled structural units, 32.9% are external and 48.0% are internal ones (Fig. 4.7.a.). The percentages reported confirm the bigger development of row buildings with shapes rather stretched and compact.



Figure 4.6. (a) Different type of buildings: isolated, row buildings and complex buildings

Analyzing the position occupied by structural units in which overturning mechanisms are activated, it is possible to notice that these mechanisms involve aggregate buildings rather than isolated ones. More precisely, within row and complex aggregates, the overturning occurs for 61.1% in the internal structural units, in facades (Fig. 4.7.b.). These walls are particularly vulnerable to this type of mechanism because of the limited connection with orthogonal walls and the lack of tie on the top.



Figure 4.7. (a) Aggregation of buildings. (b) Position of structural units involved in overturning

From the analysis of the original documents and in-situ surveys, it has been possible to go back to the historical evolution of the aggregates.

With this process, the temporal constructive phases have been identified for the different parts of the aggregate: the original elements have been recognized (the oldest ones of the entire building) as well as the portions added during the evolution of the construction. This process implies that in an aggregate only a few houses are constituted by close masonry cells. Only the perimeter walls carried out contemporarily have, for instance, a correct organization of the angular connections (Carocci, 2001).

This "critical method" allows to highlight the structural discontinuity zones, that represent high seismic vulnerability elements.

For the building stock of Castelnuovo it is possible to recognize the most ancient core of the aggregates, which corresponds to the structural units made with the oldest construction methodology. This methodology is characterized by irregular masonry textures, continuous walls from the top to the bottom, ground level wall thickness that reaches 90 cm and vault structures at that level.

Aggregates reach the actual configuration with enlargements, creation of outbuildings and raising on rear facades.

The following picture (Fig. 4.8.) shows the plans of ground level of three aggregates situated inside the perimeter.

For each structural units construction evolution and damage level are indicated. It is important to notice that original core of the aggregates have generally suffered common high damage level (D4/D5), while the structural units built in succeeding times have shown lower damages to the structural elements. The outbuildings and enlargements have usually low damage levels (D0/D1) because they are made in reinforced concrete, their conservation status is excellent and, obviously, they are separated from masonry structures.



Figure 4.8. Three aggregates: process evolution and damage level for each structural unit



Figure 4.9. Three aggregates: some photos after earthquake

5. CONCLUSION

From the analysis of the work carried out on the whole building stock of Castelnuovo it is possible to affirm that reached damage level is mainly due to two factors: intrinsic vulnerability, related to the stone masonry type with poor quality mortar and severe conservation status of buildings.

To confirm what mentioned above, it is observed that low vulnerable structures with a good conservation status have shown a good seismic behavior.

From a scientific point of view the information collected form a varied and extremely useful database. For each aggregate, starting by the structural survey and by the interpretation of the damage, it will be possible to implement an analytical model and to make safety verifications, in order to identify specific intervention techniques to plan the rehabilitation.

The application of this methodology on the whole built allows the deepening of vulnerability assessment of masonry historical buildings in aggregate for better understanding the seismic behaviour of single structural units within the aggregates.

REFERENCES

- Borghini, A., Del Monte, E., Ortolani, B. and Vignoli, A. (2011). Studio degli effetti del sisma del 06/04/2009 sulla Frazione di Castelnuovo, Comune di San Pio delle Camere (AQ). XIV Convegno Nazionale ANIDIS L'Ingegneria Sismica in Italia, Bari, Italia.
- Carocci, F.C. (2001). Guiderlines for safety and preservation of historical centres in seismic areas. *Historical Constructions*. P.B. Lourenço, P. Roca (Eds.), Guimarães, 2001.
- C.M. 617/2009. (2009). Circolare Ministeriale n.º 617 del 02/02/2009. Istruzioni per l'applicazione delle "Nuove Norme Tecniche per le Costruzioni" di cui al D.M. 14/01/2008.
- D.M. (2008). Decreto Ministeriale del 14/01/2008. Nuove Norme Tecniche per le Costruzioni.
- Del Monte, E. and Vignoli, A. (2008). In situ mechanical characterization of the mortar in masonry buildings with DRMS. 1st International RILEM Symposium on site assessment of concrete, masonry and timber structures, Varenna (CO), Italy.
- DPC-ReLUIS (2010). Linee guida per il rilievo, l'analisi ed il progetto di interventi di riparazione e consolidamento sismico di edifici in muratura in aggregato.
- Giovinazzi, S. and Lagomarsino, S. (2001). Una metodologia per l'analisi di vulnerabilità sismica del costruito. *X Convegno Nazionale ANIDIS L'Ingegneria Sismica in Italia*, Potenza – Matera, Italia.
- GNDT (2000). Manuale per la compilazione della scheda di primo livello di rilevamento danno, pronto intervento e agibilità per edifici ordinari nell'emergenza post-sismica (AeDES). Dipartimento della Protezione Civile.
- Grünthal, G. (1998). European Macroseismic Scale 1998 (EMS-98). Cahiers du Centre Européen de Géodynamique et de Séismologie, 15, Luxembourg.
- Valluzzi, M.R., Cardani, G., Binda, L. and Modena, C. (2004). Seismic vulnerability methods for masonry buildings in historical centres: validation and application for prediction analyses and intervention proposals. *Thirteenth World Conference on Eartquake Engineering*. Paper no.2765.
- Working Group CPTI (2004). Catalogo Parametrico dei Terremoti Italiani versione 2004 (CPTI04), *INGV*, Bologna. http://emidius.mi.ingv.it/CPTI04/.

Working Group MS-AQ (2010). Microzonazione sismica per la ricostruzione dell'area aquilana. Regione Abruzzo Dipartimento della Protezione Civile, L'Aquila. **Vol. III e Cd-rom**.