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Performance of masonry structures during the 2009 L'Aquila (Italy) earthquake

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ABSTRACT:
The surface magnitude 6.3 L'Aquila earthquake which struck the L'Aquila area on April 6, 2009, damaged a large number of buildings, of nearly all construction types. Its epicentre was only 7 kilometres of north-west of the city. Officially, 306 died and 1500 were seriously injured. Approximately, 15000 buildings were severely destroyed or collapsed. These buildings were representative of construction types in form and structural system to those of the same vintage found across Europe. This study concentrates on the damage suffered by masonry buildings during this earthquake, and explains why the various types of observed failures happened. Examples of various damage types, as observed by the authors during the reconnaissance visit to the stricken area are presented, along with technically substantiated description of reasons for the damages.

***Keywords:** L'Aquila earthquake, unreinforced masonry, historical buildings, failure, collapse.*

1 INTRODUCTION

As masonry is the most universally available and economical construction material, unreinforced masonry structural (URM) or non-structural components are used throughout L'Aquila. Older buildings including historical structures are mainly constructed of stone or brick masonry. A review of this seismic performance is worthwhile considering the growing interest in the mitigation of seismic hazard in existing URM buildings throughout the world.

A large portion of L'Aquila's older building stock is of URM, built in the absence of mandatory earthquake-design requirements. These older buildings were at greater risk than the new buildings not only because they have been designed no or little seismic loading requirements but also not being capable of dissipating energy through large inelastic deformations.

The main objective of this paper is to illustrate the damage suffered by masonry buildings during L'Aquila earthquake, and to explain why various types of observed failures occurred. Most lessons learned from this review are applicable and believed to have implications for the design practise under seismic excitations.

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2 EVALUATION OF GROUND MOTIONS DATA

The earthquake has been recorded by fifty eight stations operated by Italian Strong Motion Network. Besides, 113 seismometers of the INGV network recorded the earthquake. Table 1 shows the strong motion record characteristics with peak ground acceleration (PGA) values greater than 0.1g.

Table 1. Strong motion characteristics

Station code	Coordinates	Site Class	Epicentral distance (km)	PGA (cm/s^2)	PGV (cm/s)	Arias Intensity (cm/s)	Housner Intensity (cm)
AQM	42.379N, 13.349E	A	5.2	1000 (saturated)	42.18	435.4	90.1
AQV	42.377N, 13.344E	B	4.9	646.1	42.83	285.7	94.5
AQG	42.373N, 13.337E	A	4.4	506.9	35.54	137.0	92.2
AQA	42.376N, 13.339E	B	4.6	435.6	32.03	175.0	86.1
AQK	42.345N, 13.401E	B	5.6	347.2	36.21	128.9	68.1
AQU	42.354N, 13.402E	B	5.8	309.5	35.00	71.0	78.0
GSA	42.421N, 13.519E	A	14.1	149.1	9.84	44.0	17.8

Despite the relatively moderate magnitude of the L'Aquila earthquake (Mw 6.3), large PGA values were recorded, and vast amounts of damage to towns in the surrounding area were observed. The table depicts quite high PGA values with respect to the magnitude of the event. For AQM station, PGA has also saturated, which makes it impossible to use the record. Horizontal components of the motion for some of the stations are given in Figure 1 for five stations. Strong shaking duration of the earthquake (90% of the energy) is less than 10 seconds. Besides, 60% of the energy is exerted on the buildings within 3-5 seconds [1]. Therefore, it can be categorized as a short event with high PGA values that are capable of producing high spectral accelerations. One major factor in the amount of damage observed is the high vulnerability of the poorly maintained residential masonry low storey buildings that are predominant in the affected town centres. It is certain that a prolonged period of shaking with high accelerations would cause a heavier damage profile for buildings.

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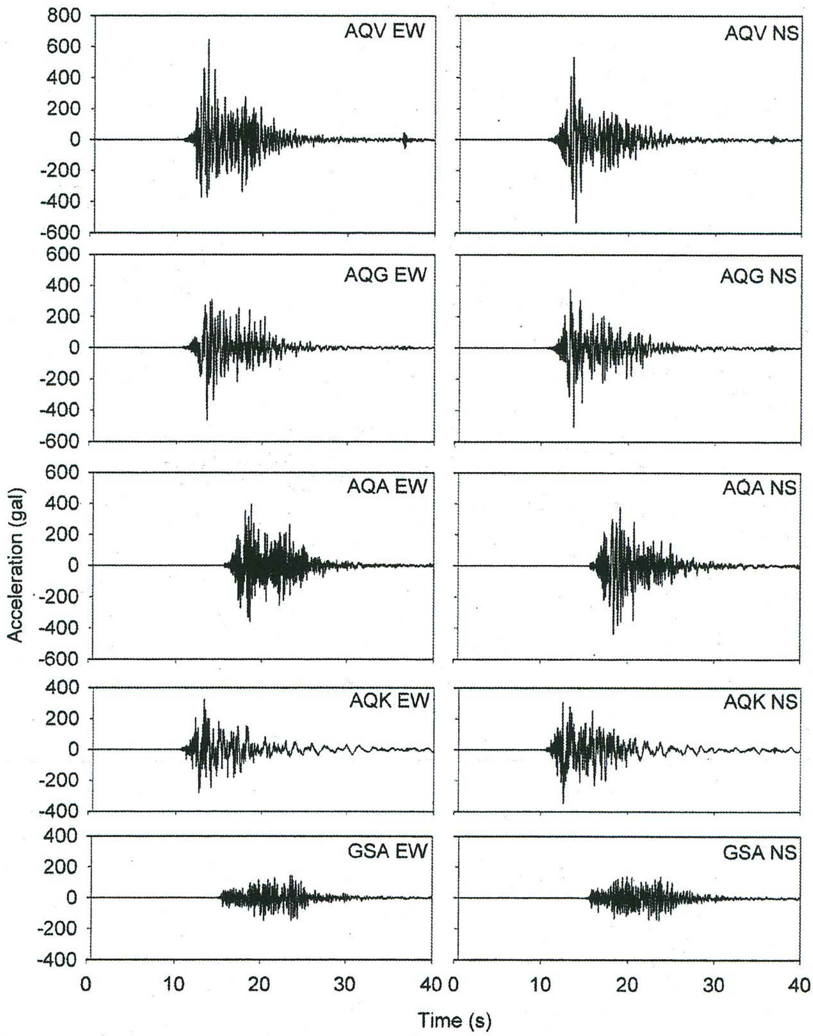

Figure 1. Corrected acceleration records for stations with PGA>0.1g (time not syncronized)

Figure 2 compares spectral acceleration values of each record and the average of them with the current design spectrum of the Italian Code (NTC2008) for rock type soils and that of 1996 Code for Category 2. The current code has greater spectral accelerations with respect to the older code. However, most of the buildings were not designed per 2008 code. Moreover, many of the buildings were non-engineered. Nevertheless, response spectrums have much higher acceleration values than both codes especially for periods less than 1.0s. This figure clearly shows that buildings were exposed to seismic forces higher than expected design forces. The average spectrum of 10 strong motion components almost doubles the spectrum of 1996 code for T<0.5s.

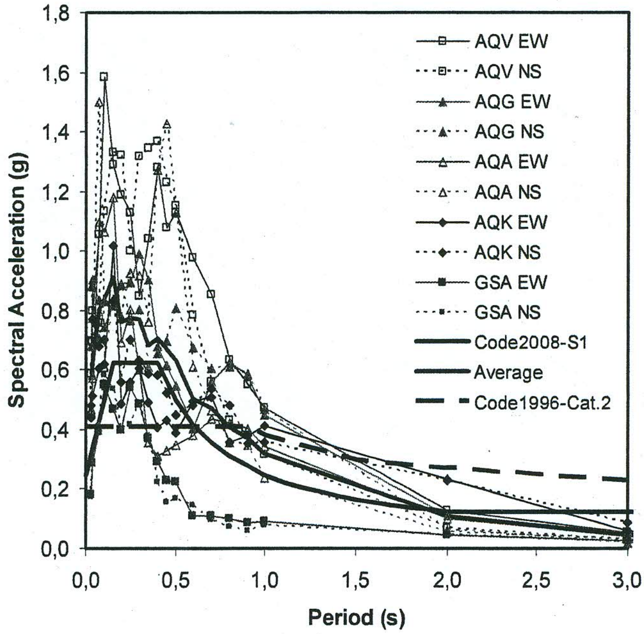

Figure 2. Response spectra of records of 5 stations for 5% damping and comparison with NTS design spectrum

3 STRUCTURAL DAMAGES

3.1. Construction and damage types observed in L'Aquila

The types of construction in the earthquake-stricken area can be grouped as;

- Low to medium-rise reinforced concrete (RC) frames with URM infills.This structure form is used for all building heights. As these URM infill walls had a dominant influence on the performance of the main structural system, a brief overview of this seismic performance is noteworthy.
- Older and historical buildings mainly constructed stone and brick masonry,
- Industrial buildings

There is a relationship between the qualities of construction materials, PGA and damage. The structural failures observed from the L'Aquila earthquake varied depending on the location, building type and the age of construction. The observed failure modes of URM buildings can be classified as follows;

- Anchorage-related failures,
- In-Plane and out-of-plane failures,
- Diaphragm-related failures.

These failure types are described in the subsections with the observed damaged buildings.

3.2. Structural damages to URM

In many of the damaged buildings, there was a total absence of anchorage of the floors, corners and roof to the walls. In the absence of anchorage, the exterior walls behave as cantilevers over the building height. Even though it is true that some friction force exits at the supports that may prevent failures in low range of earthquake excitation, the resistance between them is supposed to be small and negligible. Lack of anchorage resulted in failures in many buildings (Figure 3).

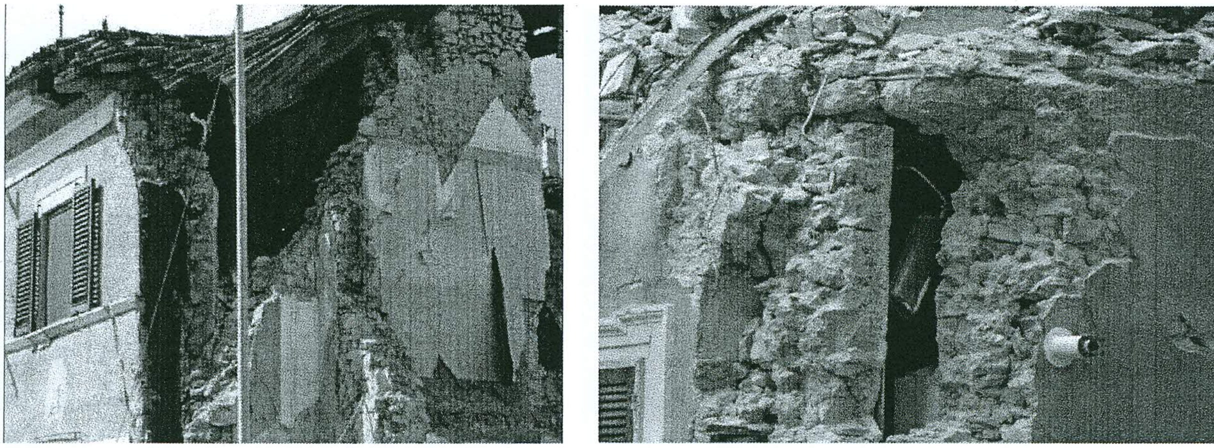

Figure 3. Failures due to the absence of anchorage between cross walls

For URM walls, shear in plane failures are common expressed by X (double-diagonal) shear cracking. Excessive shear or bending produced in-plane failures in many old buildings in L'Aquila (Figure 4a). In masonry facades where numerous window openings, spandrels and the short piers failed in shear (Figure 4b).

a) b)

Figure 4. a) In-plane shear failure of URM walls ; b) In-plane shear failure of URM pier

Beam–to-wall anchors provide out-of-plane supports to the walls. Due to the absence of sufficient strength, many of the URM buildings were most vulnerable to flexural out-of-plane failures. These kinds of failures were observed in many buildings and the gravity-load-carrying capabilities of these walls vanished (Figure 5a). Double-layer URM walls constructed with sandwiching insulation performed poorly as well: the presence of insulation prevented bond between the layers and resulted in out-of-plane failures.

Especially in historical monumental buildings, parapet failures were observed. These non-structural elements behaved as cantilever walls extending beyond the roof line, located at the top of the buildings. Generally gables of churches and similar buildings improperly anchored the roof and behaved like parapets (Figure 5b).

Figure 5. a) Out-of-plane failure of URM top-story wall ; b) Parapet failure of a historical building

Pounding against adjacent structures caused failures (Figure 6).

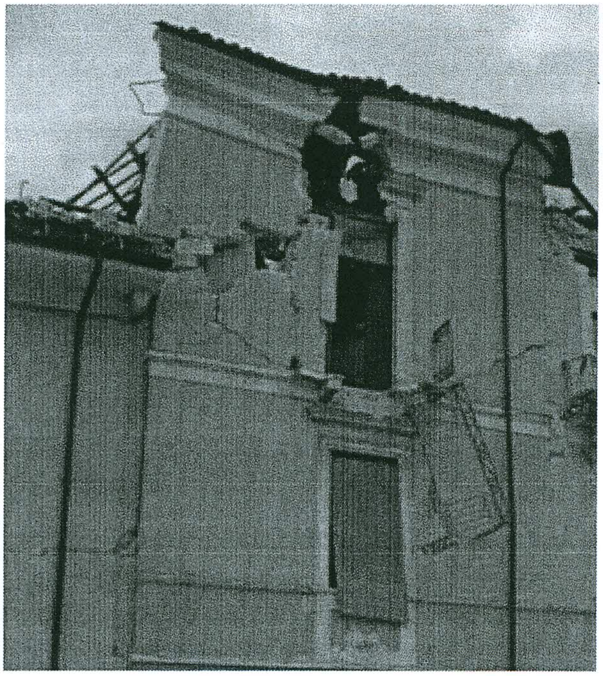

Figure 6. Pounding-induced failure

4 MASONRY WALL CONSTRUCTION TECHNIQUES

Masonry wall construction involves the laying of brick, concrete block, or stone in beds of mortar, the installation of accessory items, and sometimes reinforcement. One of the most important things is that masonry units should be placed to interlock with each other and satisfy a proper connection between crossing walls. Typical interlocking of masonry units are shown in Fig. 7.

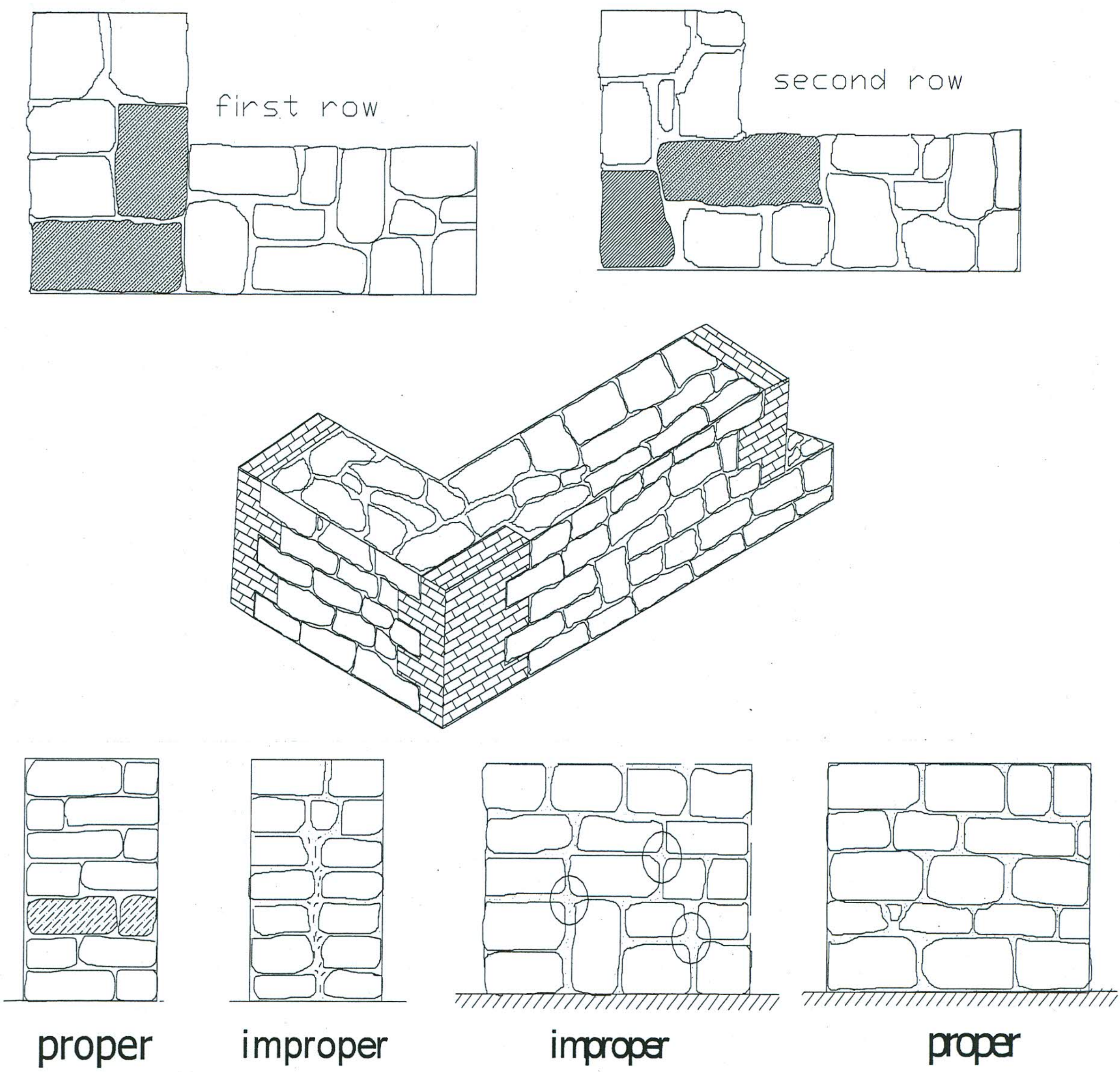

Figure 7. Typical interlocking of masonry units

Bonding beams are also important elements to satisfy the integrity of the walls. They can be either constructed from wood or reinforced concrete (Figure 8). It is always better to confine concrete with horizontal and vertical bonding elements. However, it is very crucial to construct horizontal beams.

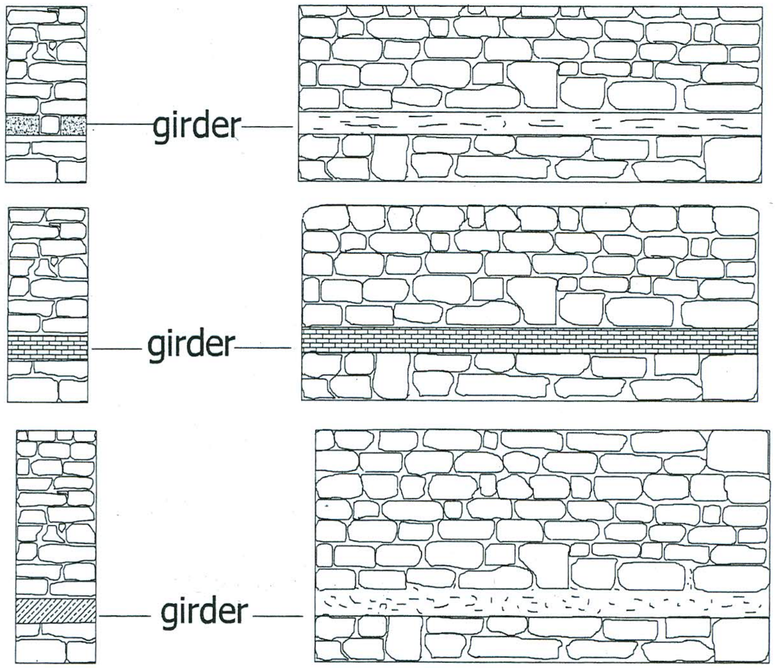

Figure 8. Bonding beams (girders) in URM walls a) Wood, b) Brick c) Reinforced Concrete

5 CONCLUSIONS

In this paper, seismic performance of existing URM buildings has been presented. The various failure modes of URM buildings have been described and illustrated. The extensive damage which occurred in L'Aquila demonstrates the potential catastrophic seismic performance of non-ductile structural systems. A large number of URM structures severely damaged and collapsed during this earthquake. However, in some instances, the behaviour of such systems was satisfactory if enough over-strength was present to ensure elastic behaviour. This good performance was observed in older URM buildings with good material and construction quality. Main reasons of extensive damages during L'Aquila Earthquake are listed as follows:

- Wall and slab thicknesses were extremly large. Therefore, seismic weight of buildings and seismic forces was too high. Similar conditions were also observed in Bingöl [2], Cameli [3] and Dogubeyazıt [4] Earthquakes in Turkey.
- Walls were formed by bad quality stones and mud mortar and not interlocked properly. Under seismic forces integrety of the wall was failed causing heavy damages. In general, masonry wall practice does not conform to the standards of seismic resistant walls.
- Heavy decoration elements on wall openings were falled and damaged many cars. Those were not fixed to the bearing walls as it should be.
- Another important problem was the lack of sufficient interlocking between crossing walls. Such a deficiency significantly reduces the out of plane resistance of the walls.
- Ratio of wall openings exceeded the acceptable limits. Lateral load capacity of such walls significantly reduces. Besides, many openings were located near to corners or crossing walls, which affects the out-of-plane failure mode undesirably.

Earthquakes that occurred over the recent decades repeatedly showed that the URM buildings cannot be ignored. For small-to-moderate earthquakes, older structures suffered considerable damage while most of the newer engineered construction survived.

In the light of the observed damage in L'Aquila, decision makers should be aware of the catastrophic nature of non-ductile structural systems when weighing options in seismic mitigation strategies. This is important because of the large inventory of existing structures constructed prior to the legislation of ductile design guidelines.

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