JRC Scientific and Technical Reports

The L'Aquila (Italy) earthquake of 6 April 2009: report and analysis from a field mission

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EUR 24684 EN - 2011

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JRC 62359

EUR 24684 EN
ISSN 1018-5593
ISBN 978-92-79-18990-6
doi:10.2788/188

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Printed in Italy

Abstract

The province of L’Aquila in central Italy was hit by a 5.8 M_L earthquake in the night of 6 April 2009. The maximum intensity was estimated at 8.5 MCS, evidenced by heavy damage or collapse of many buildings, including heritage ones. 67.500 persons were in need of assistance in the following weeks. This report presents the information collected during a field mission by means of an extensive photographic documentation, focusing on the behaviour of reinforced concrete and masonry buildings. Moreover, the evolution of the building codes in Italy is reviewed.

Acknowledgements

The authors would like to thank all people that helped them during their field mission.

In particular they want to thank Italian Authorities, the Civil Protection headed by prof. Mauro Dolce and the Fire Brigade (VVF) for their very much appreciated help and support received during the intensive surveys in the damaged areas, usually red areas where special permits were necessary to enter.

A special thank also to the colleagues from the LNEC laboratory in Lisbon, to the Global Security and Crisis Management Unit colleagues and to the former ELSA Unit Head prof. Michel Geradin.

Figure 1: The authors with the accompanying Fire Brigade and their colleagues at the command point DICOMAT nearby L’Aquila

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1. Introduction

A 5.8 M_L earthquake hit L'Aquila, capital of the Abruzzo Region in central Italy, at 3:33 A.M. local time, on 6 April 2009. The maximum intensity was estimated at 8.5 MCS and the depth of the hypocentre was about 8 km. The main earthquake was preceded by an intense seismic activity and was followed by many aftershocks.

The population affected by the earthquake crisis and assisted by the Italian Civil Protection reached 67.500 in April 2009. At that time, 40% of the assisted population was living in hotels, 16% in private houses, 44% in camps organised by the Civil Protection and 1% in spontaneous camps (DPC, 2009a).

Table 1.1 summarises the results of the damage assessment of public, private, hospital, school, military and industrial buildings, as on 3 June 2009 (DPC, 2009b). The majority of buildings (67.2%) were classified as usable (immediately, or after minor intervention), while a significant percentage was unusable. As shown in Table 1.2, the situation was worse for heritage buildings: more than half were classified as unusable and approximately one third was usable (immediately, or after minor intervention) (DPC, 2009c).

Table 1.1: Percentage (%) of buildings belonging to different damage classes (information updated on 3 June 2009)

	Type of building						
	all	private	public	hospital	military	school	industrial
Usable	53.6	53.3	55.7	43.4	75.7	52.6	60.3
Usable after intervention	13.6	13.3	16.1	34.0	18.8	27.9	16.8
Partially unusable	2.8	2.7	4.0	11.3	2.1	2.1	3.8
Temporarily unusable	1.0	1.0	1.5	1.9	0.0	2.9	0.7
Unusable	24.3	24.9	19.7	9.4	3.5	12.9	14.5
Unusable (other reason)	4.7	4.8	3.0	0.0	0.0	1.6	3.8

Table 1.2: Percentage (%) of heritage buildings belonging to different damage classes (information updated on 25 October 2009)

	all	churches	palaces	other
Usable	23,9	33,3	7,7	47,3
Usable after intervention	13,2	16,5	7,9	18,2
Partially unusable	3,0	2,9	3,1	3,6
Temporarily unusable	5,9	9,0	1,5	1,8
Unusable	51,6	37,7	74,7	23,6
Unusable (other reason)	2,4	0,5	5,1	5,5

Motivated by the magnitude of the event, the extent of the damage and the scientific interest to investigate the seismic performance of buildings, the European Laboratory for Structural Assessment (ELSA) of the Joint Research Centre (JRC) organised a field mission to the affected area. Preliminary information on the damage and the emergency management had been collected by the assessment team of the European Community Civil Protection Mechanism that supported the Italian Civil Protection in the assessment of the stability of buildings (MIC, 2009).

The main objective of the mission was the on-site assessment of the earthquake effects on different types of structures, in view of subsequent earthquake engineering studies. The studied structures belong to the following categories: recently-constructed buildings, engineered buildings constructed in the 60’s, stone masonry buildings and heritage structures (churches and other monuments mainly in the L’Aquila city centre).

The mission took place on 22 and 23 May 2009, when the immediate post-earthquake emergency was over. However, access to large parts of the visited cities was possible only if accompanied by a Fire Brigade. The two-days mission comprised the following site study visits:

- the Coppito Campus of the University of L’Aquila, where staff of the Department of Civil Engineering presented the effects of the earthquake on the University buildings;
- the local headquarters of the Civil Protection, where Prof. Mauro Dolce and some of his collaborators presented many of the issues related to the earthquake and the emergency management;
- the “red zone” of L’Aquila city centre, where most heritage structures suffered extensive damage or collapsed;
- a suburb in the north of the city of L’Aquila, where most of the buildings have been constructed recently and some where in construction at the time of the earthquake;
- the “red zones” of Paganica and Onna, two of the most affected towns.

The aim of this report is to present an overview of the most significant aspects of the event, based on the evidence collected during the field trip, on the documentation collected in preparation for the mission and on the information gathered from the experts met on the field.

Following the Introduction, Chapter 2 describes the seismic event, the geology and tectonics of the region, the historic seismicity and seismic hazard mapping. Chapter 3 deals with the performance of reinforced concrete buildings. The performance of masonry buildings, along with the role of ties and of the state of conservation, is discussed in Chapter 4. The evolution of design codes and building regulations in Italy, in relation to the most destructive earthquakes, is presented in Chapter 5. Finally, the main points of the report are summarised and some conclusions are given in Chapter 6.

2. The seismic event

2.1 GEOLOGY AND TECTONICS

The seismic event of the 6th of April 2009 affected a portion of the Apennine area (see Figure 2.1) where a complex pattern of active faults (potentially able to generate earthquakes of magnitude up to 7) is located (Galadini et al., 2009).

Figure 2.1. L’Aquila epicenter location (from wikipedia)

Even if superficially the faults can have different length, never exceeding 20 km, they have most probably a continuous origin in the deeper layer (see Figure 2.2).

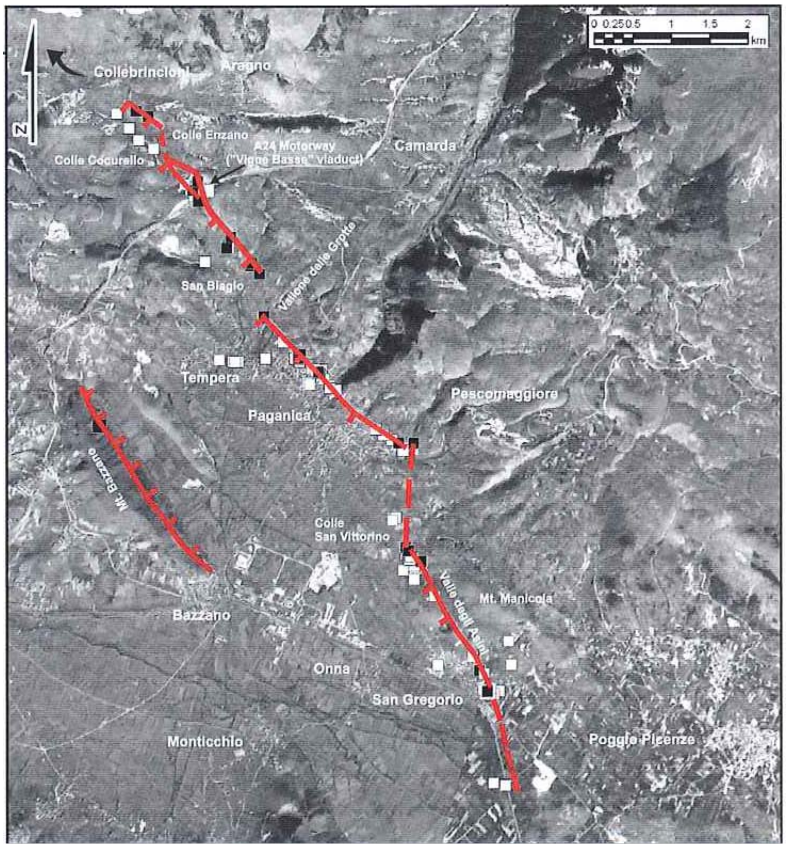

Figure 2.2: The system of faults in the L'Aquila area (Falcucci et al., 2010)

Two are the most important systems of active faults belonging to the central Apennine: the Umbrian Apennine system and the Abruzzo one. The former concerns the southern part of the Umbria region and includes the Norcia fault and the Mt. Vettore one. The Norcia fault has been responsible for earthquakes with magnitude greater than 5: the 1328, 1599, 1730, 1859 and 1979 earthquakes (magnitude between 5.5 and 5.9) and the 1703 earthquake (magnitude 6.7). No relevant earthquake can instead be associated to the Mt.Vettore fault.

In the Abruzzo Apennine it is possible to identify a western part, with three active systems of faults (from the Aterno valley on the north to the Fucino valley on the south), responsible for the 1703 Aterno earthquake of M_w = 6.7 and the 1915 Fucino event of M_w = 7.0, and a central-oriental zone, with five systems of faults including the Paganica fault responsible for the 2009 event.

The Paganica fault, in the NW-SE direction of the Appenines, has a length of 11-18 km, depending on whether the Mt. Stabiata (north) and San Demetrio ne' Vestini faults (south) are considered part of it. On the east, the fault delimits an alluvial valley. According to the Italian National Institute of Geophysics and Volcanology, the 6 April 2009 main shock took place along a normal fault oriented NW-SE: several fractures in the central zone of the fault presented both horizontal and vertical displacements, while in the southern zone, only horizontal kinematism was observed.

2.2 HISTORICAL SEISMICITY

The city of L'Aquila has already suffered strong seismic events (Boschi et al., 2009).

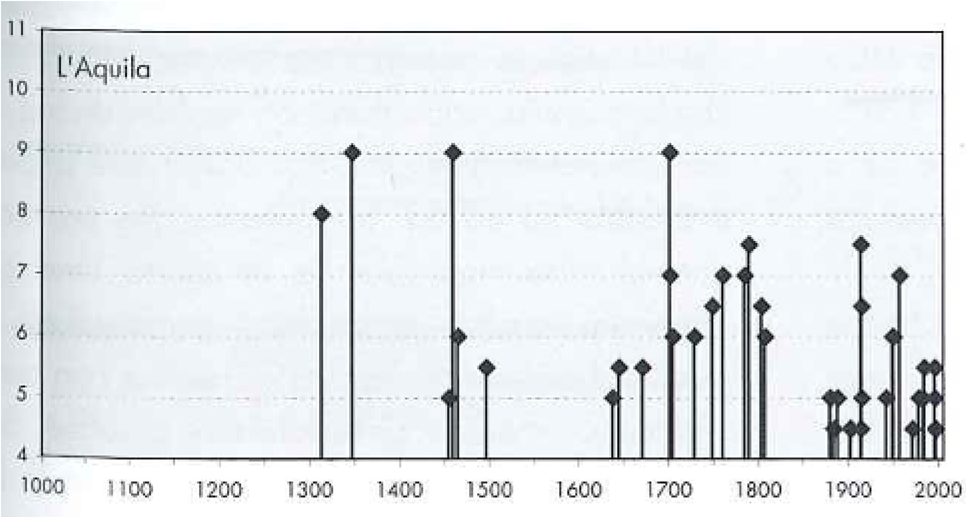

Figure 2.3: Most relevant seismic events in L’Aquila (intensity-years) (Stucchi et al., 2009)

The most severe ones were in 1315, 1349, 1461 and 1703 (Stucchi et al., 2009) (see Figure 2.3 and Figure 2.4).

Not much information about the earthquake of 1315 is available, while it is known that the 1349 event was caused by the activity of several sources.

An event with characteristics similar to the 2009 recent earthquake occurred in 1461 and strongly damaged not only L’Aquila but also Onna, Poggio Piacenze and Castelnuovo.

More information is available concerning the events that occurred in the 18th century: on the 14th of January 1703 L’Aquila was partially damaged by an earthquake with epicentre in Norcia; some days later, on the 2nd of February, a stronger event affected directly the city and considerably increased the pre-existing damage. Few years later, in 1706, another event, this time located in the Sulmona/Maella area aggravated the damage not yet repaired.

In the recent past, we can mention the 1915 Fucino event, the events located in the Gran Sasso area (1950 and 1951) and in 1958 a less intensive earthquake located in Onna.

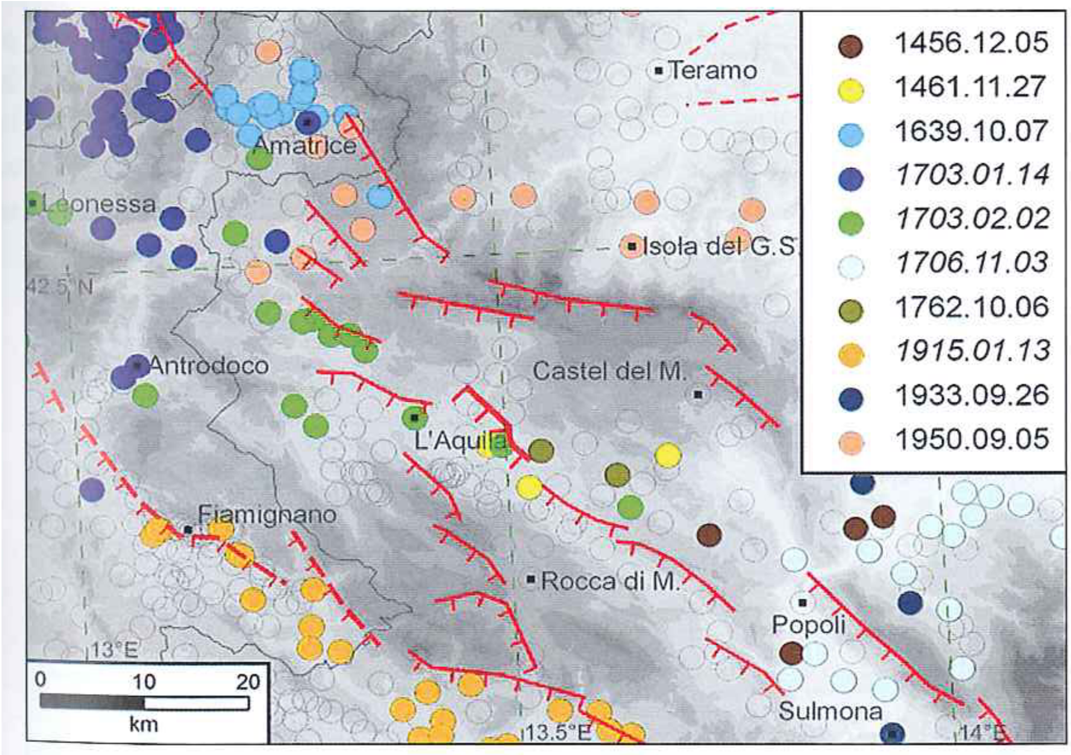

Figure 2.4: Historical seismicity of L'Aquila (Stucchi et al., 2009)

2.3 SEISMIC HAZARD MAPPING

When in 1927 the Italian territory was divided in seismic zones, organized in a scale from 1 to 4 (from lowest to highest seismicity) depending on the level of hazard, L'Aquila was considered in Zone 2. A part of the surrounding municipalities were included only later, in 1962, being always classified as Zone 2. In 2003 a new task force of experts, lead by the Italian Civil Protection, confirmed the Zone 2 classification for L'Aquila, while some municipalities, namely Barete, Cagnono, Amiterno, Capitignano, Montereale, Pizzoli and Tornimparte, were moved into Zone 1. This new classification was also adopted in the OPCM 3274 (for a briefly explain on what OPCM is refer to the relevant section in Chapter 4) emanated in the same year.

One year later, the Italian National Institute of Geophysics and Volcanology published a new seismic hazard map (MPS04, http://zonesismiche.mi.ingv.it) elaborated according to the criteria of the OPCM 3274. In this new map, L'Aquila was included in the zone of high hazard, with a high probability of occurrence (10% probability of excedence in 50 years, rigid soil, v_{s30}>800m/s) of an event with peak ground acceleration greater than 0.25.

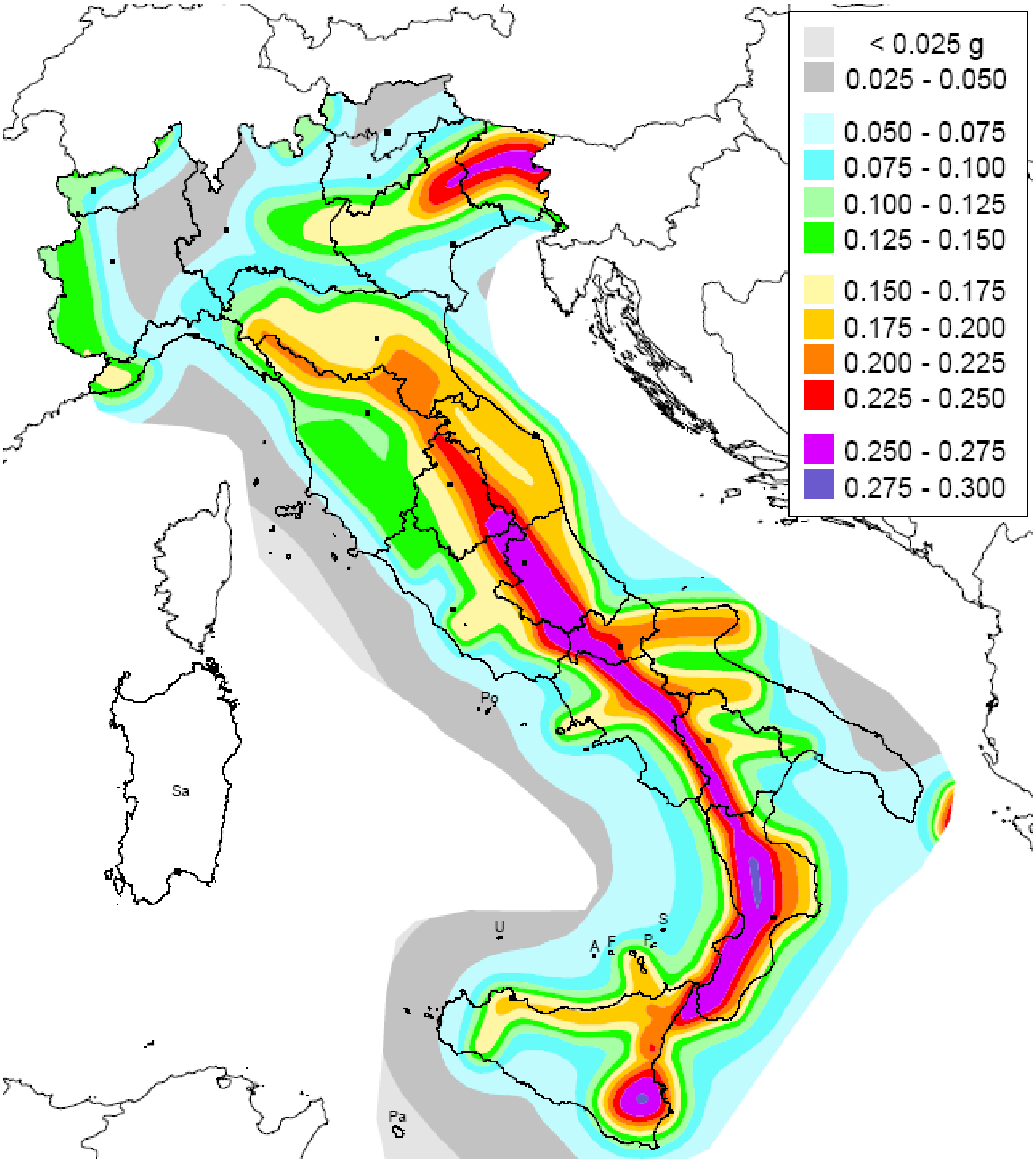

Figure 2.5: Seismic hazard map - MPS04 (http://zonesismiche.mi.ingv.it).

In (Merletti et al., 2008), according to the seismic hazard map - MPS04 (see Figure 2.5), the Apennine area is divided in three zones (ZS 915, ZS 919, ZS 923). According to this classification, the ZS 923 zone, that includes L'Aquila municipality, is characterized by a hypocentral depth of 8-12 km, normal fault mechanism and maximum magnitude of 7.0. The 6th of April 2009 event is in full agreement with this estimation.

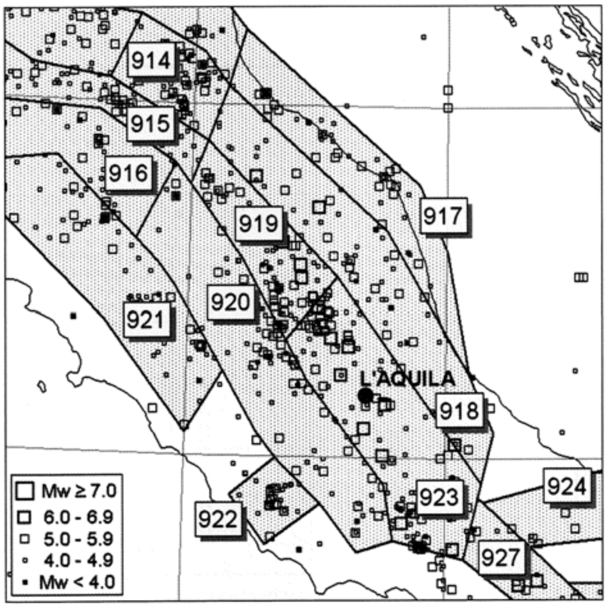

Figure 2.6: Hazard mapping according to Merletti et al., 2008

2.4 STRONG MOTION RECORDS

Four accelerometric stations (AQV, AQA, AQG, AQK) were located within the surface projection of the fault and recorded peak values ranging from 0.4 to 0.6g. Peak computed ground velocities were estimated at around 35 cm/s. The stations were located in the Aterno river valley, NW of the city of L’Aquila and in the city itself. The recorded motions are characterised by short durations (less than 10s) and high peak accelerations both in the horizontal and vertical directions. In some cases, peak vertical accelerations are higher than the horizontal ones. Also, the strong portions of vertical and horizontal motions occurred almost simultaneously due to the short travel paths of P and S waves from the fault to the ground surface. This is evident in Figure 2.7, where the strong horizontal motion appears to start only about 1s after the vertical one, with a predominant period of 0.4-0.6s. These features can be particularly damaging to weak non-ductile systems, such as the old masonry structures in the area (Simonelli, 2009).

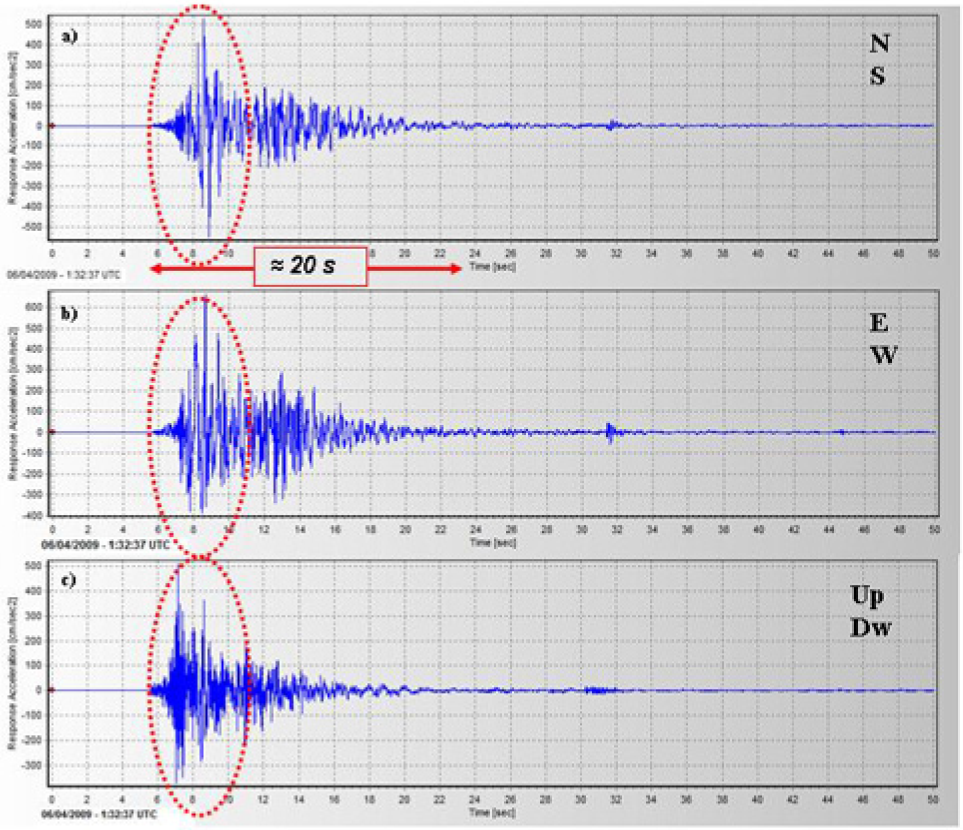

Figure 2.7: AQV station records (NS, EW and V direction) (Simonelli, 2009)

3. Performance of reinforced concrete buildings

3.1 CLASSIFICATION OF REINFORCED CONCRETE BUILDINGS

Reinforced concrete buildings constitute 22% of the residential building stock of the L'Aquila Province (ISTAT, 2004). Detailed information on the state of conservation and the year of construction of reinforced concrete residential buildings, as collected at the 2001 census is given in Table 3.1, where it is shown that 95% of the buildings are in excellent or good state. Furthermore, structural repairs have been performed during the 90s only in 6% of the residential building in the Abruzzo Region.

The majority (66%) of reinforced concrete buildings outside the historical centre of L'Aquila city are single-family residential buildings (Liel & Lynch, 2009). Other uses include multi-family residential (21%), multi-family residential with commercial activities (7%), commercial and retail (4%), industrial (1%) and public (less than 1%).

It is common to classify buildings by the period of construction, which relates to the codes applicable at that time. As discussed in detail in chapter 5, the first law on seismic design of structures passed in Italy in 1974 and is considered to provide insufficient protection of structures against earthquakes. A law that incorporated the state-of-the-art was introduced in 1996 and has been updated several times.

In this chapter, buildings built before 1996 are classified as old and buildings built after 1996 are classified as new. Old buildings comprise those constructed before 1974, without any seismic provisions, and those constructed from 1974 to 1996, with insufficient seismic provisions. The buildings are classified as new or old based on architectural/typological and structural characteristics, where the latter were possible to observe during the field mission.

Table 3.1: Number of RC residential buildings in L'Aquila Province (ISTAT, 2004)

	State of conservation				
Year of construction	Excellent	Good	Poor	Bad	Total
before 1919	0	0	0	0	0
1919 – 1945	157	546	152	7	862
1946 – 1961	309	1128	242	17	1696
1962 – 1971	934	2365	261	9	3569
1972 – 1981	2443	3776	367	9	6595
1982 – 1991	3506	2925	159	18	6608
after 1991	3077	859	40	5	3981
Total	10426	11599	1221	65	23311

3.2 OLD REINFORCED CONCRETE BUILDINGS

Most of the reinforced concrete buildings examined during the field mission are classified as old. This is verified by the data in Table 3.1 which shows that old buildings are more than 80% of the stock. Old buildings are mostly private houses and apartment blocks with 2-5 storeys, often detached from adjacent buildings. Because of the topography, many of the old buildings are built on slopes. The complex of the regional hospital comprises also some old buildings.

Most of the old reinforced concrete buildings suffered serious damage and a considerable number collapsed, in some cases reduced to rubble. The types of damage observed include: partial or total collapse of soft storeys, shear damage of short columns, damage of beam-column joints, diagonal cracking and out-of-plane collapse of masonry walls. In the following, examples of the observed damage are illustrated.

Figure 3.1a shows two adjacent buildings with floors not coinciding in elevation, which is an example of insufficient conceptual design. As a result of pounding, the reinforced concrete frame was severely damaged at the storey that corresponds to the roof of the stiffer masonry building.

It was common practice in the past to arrange frames in one of the main directions of the building, as show in Figure 3.1b, which resulted in low strength and stiffness in the other direction. This building was probably excited mainly in the strong direction, as evidenced also by the out-of-plane collapse of the external walls in the weak direction.

Figure 3.2a shows a 4-storey building before the earthquake (source: Google Maps). In addition to the open ground storey, the slabs of each bay were constructed at different heights so as to follow the natural slope. These irregularities in elevation contributed to the collapse shown in Figure 3.2b, although other seismic deficiencies, such as use of smooth rebars and lack of stirrups, were observed. It is noted that the part of the building that was standing on level ground (left side of Figure 3.2b) did not collapse.

(a) (b)

Figure 3.1: Examples of insufficient conceptual designl.

(a) (source: Google StreetView © 2010 Google)

(b)

Figure 3.2: Damage due to irregularities in elevation

The effect of regularity in plan and in elevation on the damage levels of reinforced concrete buildings located outside the historical centre of the city of L'Aquila has been studied (Liel & Lynch, 2009) and is summarised in Table 3.2. Regular buildings suffered in general less damage than irregular ones. In detail, negligible or insignificant damage was observed in 70% and moderate or higher damage in 30% of regular buildings, whereas the values for irregular buildings were 40% and 60% respectively.

Detailing of longitudinal and transverse reinforcement did not conform to requirements that ensure local ductility of structural elements. Smooth rebars were used in most of the damaged buildings and were therefore pulled out of the concrete, as shown in Figure 3.3a. Another common feature was the presence of hooks at the end of the rebars, which may not provide sufficient anchoring. In the case of external joints it was observed that the horizontal rebars with hooks were pushing the vertical rebars and the concrete cover out of the joint, Figure 3.3b. The absence of transverse reinforcement resulted in buckling of vertical rebars, Figure 3.3c, lack of confinement of concrete in the critical regions, Figure 3.3d, as well as reduced shear resistance.

Table 3.2: Percentage of regular and irregular RC buildings belonging to different damage classes (Liel & Lynch, 2009)

	Plan		Elevation	
Damage level	Irregular	Regular	Irregular	Regular
Negligible	26.1	32.4	23.5	33.7
Insignificant	34.8	37.2	36.5	37.2
Moderate	32.2	17.4	25.2	19.8
Heavy	7.0	12.8	14.8	9.0
Collapse	0.0	0.3	0.0	0.3

(a) (b) (c) (d)

Figure 3.3: Insufficient detailing of reinforcement

(a) (b) (c)

Figure 3.4: Damage to beam-column joints

Shear damage of a joint, evidenced by diagonal cracks, is shown in Figure 3.4a. In the majority of the examined old buildings, there were no stirrups within the joint and very few in the critical regions of framing beams and columns. Splicing of longitudinal rebars was often done within the joint, Figure 3.4b. Sliding failure was commonly observed at the cross-section at the top of columns where the casting of concrete was interrupted, Figure 3.4c. This could also be partially due to the impulse-like shaking because of the small epicentral distance.

Figure 3.5: Damage of masonry infills

Diagonal cracking, separation from beams and columns and partial collapse was observed on many masonry infills, e.g. Figure 3.5a. A recurrent feature was the continuous façade or envelope of buildings that behaved like a free-standing masonry wall independent of the frame structure but was not designed as such. Figure 3.5b shows diagonal cracking at the base of a 4-storey high external wall. Similar damage of masonry infills was observed also in new reinforced concrete frames and will be discussed in the following section.

Furthermore, out-of-plane collapse of exterior masonry walls occurred frequently. This was due to the local building practice that did not guarantee stability of the infills. External walls consisted of two leaves without any connection, or connected through a few masonry units, not properly anchored in both leaves. Figure 3.5c shows such a wall, where the external leaf has collapsed. Continuous masonry envelopes were constructed also in two leaves with the external one resting partially on the beam and partially on a thinner layer of masonry units that covered the face of the beam, as shown in Figure 3.5d.

Figure 3.5e shows the building that housed the First Aid unit of the L’Aquila regional hospital. A masonry wall, reportedly carrying the hospital sign (Fanale et al, 2009), was running along the façade of the building. This wall was simply resting on the beam and lacked any lateral support along its 20-25 m and collapsed out-of-plane during the earthquake.

(a) (b)

(c) (d)

Figure 3.6: Lack of maintenance and low quality of execution and materials

Figure 3.6a shows one of the many examples of corroded longitudinal reinforcement which is attributed to insufficient concrete cover and lack of maintenance. Low quality of execution is also evidenced in Figure 3.6b which shows a beam with practically no concrete cover and concentration of aggregates at the bottom flange. Figure 3.6c shows a cross-section of a collapsed element where low quality of concrete is obvious. A corner joint is shown in Figure 3.6d, where the inappropriate anchoring and splicing of longitudinal reinforcement, the lack of stirrups and the concentration of aggregates at the bottom of the joint are shown.

3.3 NEW REINFORCED CONCRETE BUILDINGS

New reinforced concrete buildings are mainly located outside the centre and in the outskirts of the city of L'Aquila. They are 2-storey semi-detached houses or 5-6 storey apartment blocks. A number of buildings were recently completed or were under construction at the time of the field mission. There are also public, office and commercial buildings that externally showed no evidence of damage. Office and commercial buildings were generally operational at the time of the visit, whereas some public buildings were used by the Civil Protection as management centres.

(a) (b)

Figure 3.7: Damage of masonry infills

(a) (b) (c) (d)

Figure 3.8: Damage of continuous masonry façades

The overall performance of new reinforced concrete buildings was superior to that of older ones. None of the new reinforced concrete buildings that were visited during the field mission had collapsed. Extensive damage of the masonry infills and very limited, if any, damage of load-bearing elements was observed. Figure 3.7 shows typical diagonal cracking of internal and external infills of a building under construction. Such damage, which requires costly repair, was observed in the majority of the new reinforced concrete buildings. The fact that this type of damage occurred to such extent in new buildings calls for a better consideration of the non-structural elements in the design and construction procedure.

Continuous masonry façades were common also in new reinforced concrete buildings, due to a combination of aesthetic and architectural reasons, requirements for thermal insulation as well as local building tradition. As in older buildings, façades were constructed as two-leaf walls that create a continuous envelope around the building. Due to the lack of connection between the leaves, out-of-plane collapse was frequent, as shown in Figures 3.8a and 3.8b. This type of damage is a potential cause of injury for people as well as damage to assets and installations. It is reported that collapsed infills blocked emergency exits in public buildings and that those buildings could not be used after the earthquake, even though there was no other damage.

(a) (b)

Figure 3.9: Transverse reinforcement in new reinforced concrete buildings

Figure 3.10: New reinforced concrete building with irregularities in elevation

Part of a building in the Coppito Campus of the University of L’Aquila is shown in Figure 3.8c. The building is composed of modules, as the one shown in the figure, arranged in a V-shape in plan. Part of the envelope of the building consists of a 2-storey stone masonry wall that in many cases collapsed partially, due to pounding with the reinforced concrete frame. Apart from that, the buildings in the campus suffered minor damage mainly of non-structural elements and at the time of the visit were used by the Civil Protection and some Schools of the University.

The other common type of damage to masonry façades was diagonal cracking. Figure 3.8d shows a continuous external masonry wall that extends along the six storeys of the building and apparently lacks any horizontal or vertical confining element. It was most probably constructed without any previous verification of its resistance to lateral loading. This wall actually behaved as a cantilever with some lateral restrain provided by the parapet of the balconies. Similar damage was observed in several new reinforced concrete buildings.

Figure 3.9a shows a close-up view of a column critical region in a new reinforced concrete building. The stirrups are made of smooth rebars of small diameter, with 90-degrees hooks and large spacing. As a result of insufficient detailing, the stirrups are open and the longitudinal rebars are buckled. Figure 3.9b shows similar damage of a column with largely-spaced stirrups and no differentiation within the critical region.

Some new reinforced buildings were constructed without respecting certain principles of conceptual design. Figure 3.10 shows a 6-storey residential building that was under construction when the earthquake occurred. At one extremity of the building the slabs of the first and second storey are interrupted to create a 3-storey high open space. The two last storeys extend outside the perimeter of the lower storeys. Columns in this part do not continue to the foundation, but they rest on cantilever beams. Moreover, the beams of the internal frames in the shorter direction are embedded into the slabs, creating a structural system with different stiffness in the two main directions. The construction site was not accessible and therefore it was not possible to closely examine the state of the structure. According to modern seismic codes, such irregularities should be avoided.

Within a study of the vulnerability of private buildings in central and south Italy (Di Pasquale et al, 2000), information about the typological characteristics of buildings constructed during different time periods was collected. It was observed that modern reinforced concrete buildings with seismic design are very similar to older ones as regards regularity and load-resisting system and it was concluded that the construction tradition established in the 60s and 70s resists to the more restrictive provisions deriving from scientific research and experience of recent earthquakes.

3.4 CONSIDERATIONS REGARDING THE DESIGN CODES

The Decree of the Ministry for Public Works of 16/1/1996 (LL.PP., 1996) is applicable for the design of the buildings discussed in the previous. The section of the Decree dealing with structural analysis and verifications introduces for the first time limit-state design but does not consider non-structural elements except in the case of retrofit of existing structures. However, certain guidelines for the modelling of reinforced concrete structures, e.g. applicability of simplified analysis methods, torsional effects and effect of masonry infills, are deemed outdated or unclear (Dolce, 1998). Annex 1 of the Decree contains provisions for the geometry and reinforcement of columns, beams, walls and joints, aiming to achieve a ductile behaviour of the structure. Such provisions are similar to those of modern seismic design codes (De Luca & Realfonzo, 1998). The previous remarks may explain the occurrence of damage to non-structural elements and perhaps also conceptual weaknesses, but do not justify insufficient detailing.

Eurocode 8 (CEN, 2004), that since March 2010 is the only Standard applicable for the design of structures for earthquake resistance in the European Union, covers all aspects related to masonry infills. To avoid brittle failure, premature disintegration and out-of-plane collapse of masonry panels, appropriate measures are required, such as light wire meshes anchored on one face of the wall, ties fixed to the columns and cast into the bedding planes of the masonry, concrete posts and belts across the panels. Continuous envelopes are treated as engineered masonry and they should be designed according to the provisions for confined masonry. Furthermore, it is required to perform the structural analysis and design with due consideration of the effects of masonry on the structural irregularity and of the local effects due to the frame-infill interaction.

4. Performance of masonry buildings

4.1 CLASSIFICATION OF MASONRY BUILDINGS

Masonry buildings constitute 71% of the residential building stock of the L'Aquila Province and 61% in the city of L'Aquila (ISTAT, 2004). Detailed information on the state of conservation and the year of construction of masonry residential buildings, as collected at the 2001 census is given in Table 4.1, where it is shown that 71% of the buildings are in excellent or good state.

As already said in chapter 3, it is common to classify buildings by the period of construction, which relates to the codes applicable at that time. Similarly to chapter 3, buildings built before 1996 are classified as old and buildings built after 1996 are classified as new. The buildings are classified as new or old based on architectural/typological and structural characteristics, where the latter were possible to observe during the field mission.

Table 4.1: Number of masonry residential buildings in L'Aquila Province (ISTAT, 2004)

	State of conservation				
Year of construction	Excellent	Good	Poor	Bad	Total
before 1919	7034	36529	23778	3361	70702
1919 – 1945	3624	22252	14716	1681	42273
1946 – 1961	4302	23670	11999	1011	40982
1962 – 1971	5569	23783	6430	264	36046
1972 – 1981	6742	17373	2686	74	26875
1982 – 1991	4179	6318	696	30	11223
after 1991	2452	1620	211	16	4299
Total	33902	131545	60516	6437	232400

Since the inspected historical centre of L'Aquila is mainly constituted by old masonry buildings, the following description is targeted on this buildings category only.

4.2 OLD MASONRY BUILDINGS

As already mentioned in the previous section, the visited areas were the historical centre of L'Aquila, its surroundings and the small villages of Coppito, Onna and Paganica. They are characterised by very different types of buildings: the historical centre of L'Aquila is mainly constituted of noble palaces and important buildings, while buildings in Coppito and Paganica are mainly popular houses. Onna was mainly constituted of shepherd houses, constructed with very poor materials, especially round stones with a large usage of mortar of bad quality.

4.2.1 L’Aquila

The historical centre of L’Aquila is almost entirely constituted of masonry buildings. Many of them are palaces or important houses. Churches and monuments are disseminated almost in every road, especially on the mains squares. The observed level of damage sensibly varies with the construction type, the apparent conservation state of the building and the presence of protection devices (i.e. steel ties). Several kinds of damage have been observed.

Figure 4.1a shows the pounding among two adjacent buildings. The earthquake has revealed the discontinuity between the two structures. Because of their continuous façade, in fact, before the earthquake they should appear as a whole construction.

Pounding had more destructive effects on buildings with different heights, as for example in Figure 4.1b. Damage is evident on the lower building on the left where non-structural elements of the roof were destroyed and collapsed (note that the left building has a flexible wood roof, this justifies the fact that the right building suffered only minor damages).

Figure 4.1c shows the effects of the earthquake on the corner of an important palace (the national library): when not properly connected to the rest of the building, corners often suffer important damage or even total expulsion.

(a) pounding between buildings

(b) pounding between buildings

(c) damage at corners

(d) retaining wall

Figure 4.1: L’Aquila – Example of damages

Figure 4.1d is representative of another problem not directly related to buildings: the stability of the retaining walls. L’Aquila is constructed on a hill, so there was very often the need to build retaining walls to support the buildings foundations. Since these walls are often constructed in masonry without any special provision for earthquakes, most of them have collapsed.

(a) balcony and shutter (b) tiles

Figure 4.2: L’Aquila – Non-structural damages

Non-structural damages have also an important role in the safety issue. Figure 4.2 shows some examples of danger for pedestrians. In Figure 4.2a the balcony has partially collapsed and the shutter leaning against it is in a very unsafe equilibrium. Figure 4.2b shows the tiles of an old roof: they have slid and are now leaning around the very margin. Therefore, at the time of the visit, not only the risk of total collapse of buildings, but also risks due to non-structural damage made the centre of the city of L’Aquila not accessible if not assisted by the Fire Brigades.

4.2.2 Coppito

The small village of Coppito stands some kilometres far from L’Aquila. Its origin is much more modest than the city of L’Aquila and this reflects in the type and quality of buildings. There are mainly old masonry buildings, usually with 2 or 3 floors, sometimes restored and often in a quite bad conservation state. Examples of the worst cases are shown in Figure 4.3.

A large amount of the buildings suffered damages mainly caused by incorrect original design or following retrofitting. Figure 4.4a gives an example of a heavy concrete roof constructed on an old masonry building. This roof has probably substituted a lighter wood one, but in parallel no effort has been done to increase the resistance of the load-bearing walls. The increased mass of the new roof caused lateral forces exceeding the masonry strength and causing collapse of the walls. Figure 4.4b shows the collapse of an arch overhanging a door. The arch was not properly connected to the wall. Figure 4.4c is an example of the effect of not properly connected corners of buildings. Figure 4.4d evidences that one portion of the building was adjunct to the other one without properly connecting them together, even if the presence of steel ties has prevented the house from more serious damages.

Figure 4.3: Coppito – Very poor quality of masonry

(a) heavy concrete roof (b) collapsed arch

(c) not properly connected corners (d) not properly connected buildings

Figure 4.4: Coppito - Examples of insufficient conceptual design

Non-structural damages were also frequent. Figure 4.5a shows a tilted chimney in the surrounding of the Rex Romoli buildings on a hill nearby Coppito and Figure 4.5b shows a chimney with the upper part completely collapsed. Figure 4.5c evidences the collapse of a portion of a stone non-structural wall of the Rex Romoli, while the concrete structural core of the wall resisted well to the earthquake. Similar damages were observed in other corner positions. Figure 4.5d shows the damage in the infill between the window and the door of a two-storey house.

(a) tilted chimney

(b) damaged chimney

(c) collapsed wall

(d) damaged infill wall

Figure 4.5: Coppito – Non-structural damages

4.2.3 Onna

The village of Onna suffered very extensive damage and was almost completely destroyed. Only some buildings survived: the crèche and some recent private houses.

The buildings in the village of Onna are generally small housing units with one or two storeys, rarely three. Most of them are masonry buildings with structural walls and wooden simply supported slabs or roofs. Masonry is also the material of the main church.

In general the quality of masonry buildings was not good and very often the original wooden roof and slabs were substituted with heavier concrete ones. Even for restored houses the masonry quality remains very low, with very poor mortar in an inhomogeneous matrix. The same quality of materials and of construction techniques could be observed in historical buildings. It is important to mention that Onna was a poor village of shepherds on one of the "vie della transumanza", the L'Aquila-Foggia ancient road on which shepherds seasonally migrated with their flocks.

Figure 4.6a shows the effect of a very heavy concrete roof placed on bad quality masonry: the forces and the horizontal displacements generated by the movement of its large mass caused the complete destruction of the structural wall of the building. The bad quality of masonry can be seen in Figure 4.6b, where an entrance arch partially collapsed.

Only a very limited number of buildings seemed to have steel ties passing through the floors and anchored to the façade of the buildings. These ties, if well designed and located, have the positive effect of increasing the global stiffness, generating a "rigid-box" behaviour of the structure, preventing the separation and out-of-plane collapse of the façades and the loss of support of the slabs and the roofs. In most of the buildings in Onna, the presence of ties generated no positive effects because of the extremely bad quality of the masonry that caused severe local damage or complete collapse at the anchor point of the steel ties (Figure 4.6c).

(a) heavy concrete roof

(b) bad masonry quality

(c) heavy concrete roof

(d) collapsed and undamaged buildings

Figure 4.6: Onna – damaged buildings

Some recent buildings resisted very well to the earthquake. Figure 4.6d gives an indubitable example of how damage is related to both the earthquake intensity and the building vulnerability: the building on the left completely collapsed, while the house in the centre of the photo has resisted very well to the earthquake.

4.2.4 Paganica

Similarly to the village of Onna, also in Paganica houses have usually a ground floor with two upper storeys, rarely three. They are masonry buildings with structural walls and wooden slabs or roofs.

Masonry is also the material of the churches. In general the quality of masonry buildings is poor even for restored ones. Several buildings present traces of additions (Figure 4.7a) and recently-constructed heavy concrete roofs (Figure 4.7b).

The quality of masonry varies from round stones with poor mortar (Figure 4.8a) to large and well squared stone blocks (Figure 4.8b). The Matrice church also has steel ties, strengthened corners and a simpler (and less vulnerable) configuration. The difference in the damage level is evident.

(a) addition without proper anchorage

(b) heavy concrete roof

Figure 4.7: Paganica – example of damages

(a) bad quality masonry of the Concezione church

(b) good quality masonry of the Matrice church

Figure 4.8: Paganica – masonry quality

4.2.5 Churches

Churches suffered extensive damage both in L’Aquila and in the surrounding villages. Figure 4.9 gives some examples of the damaged churches in L’Aquila. The localisation of the churches is shown in Figure 4.10.

(a) Sant’Agostino

(b) San Francesco di Paola

(c) San Bernardino (drum)

(d) Santa Maria Paganica

(e) Duomo

(f) Duomo

Figure 4.9: Churches in L’Aquila

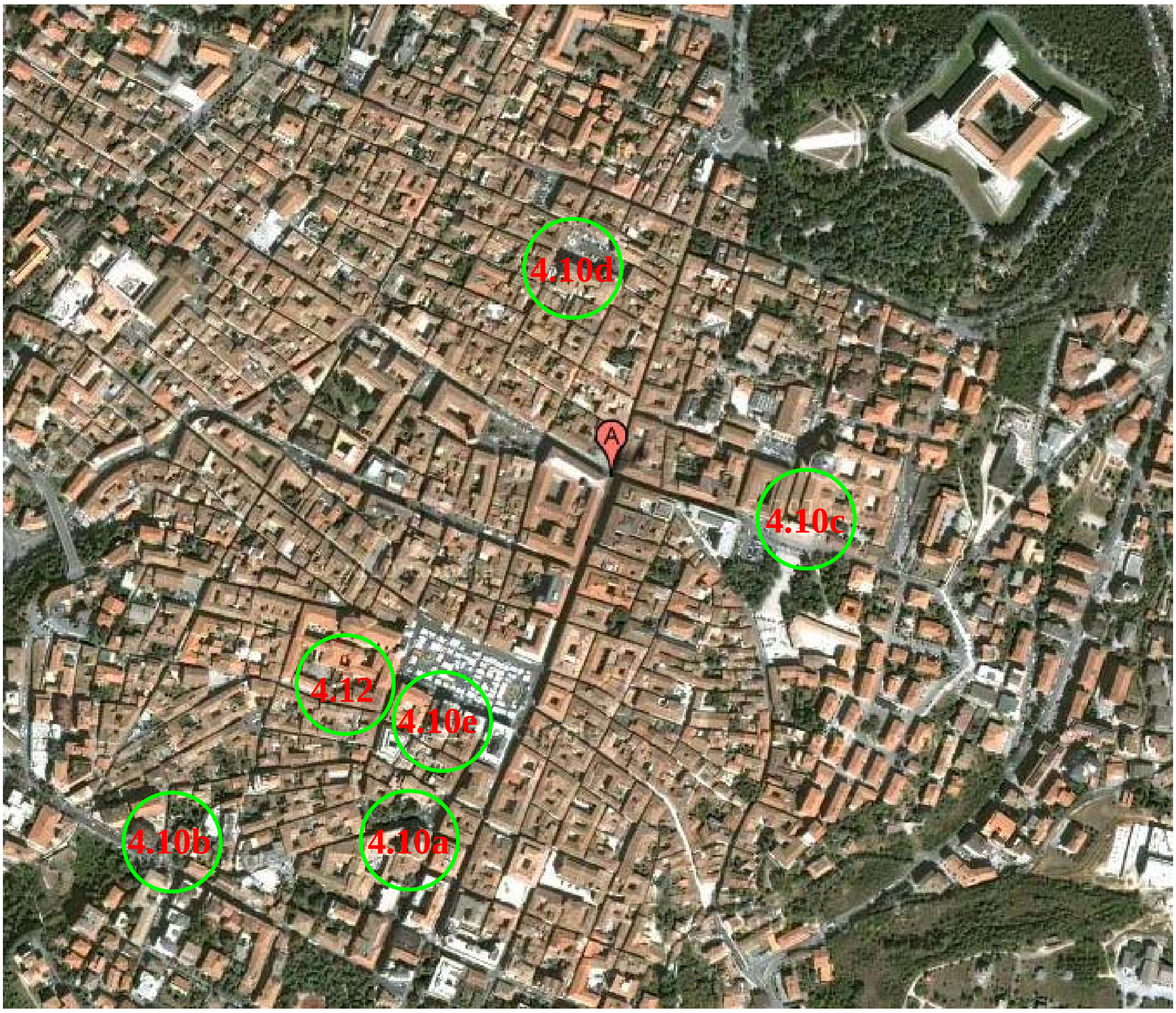

Figure 4.10: Churches localisation in L'Aquila (source: Google Maps © 2010 Google)

The church of Sant'Agostino (Figure 4.9a) suffered the collapse of the bell tower and severe damages at the drum. The church of San Francesco di Paola (Figure 4.9b) has the upper part of the façade destroyed and damages to the roof. The church of San Bernardino (Figure 4.9c) had the façade completely saved, but its drum suffered extensive cracks. The church of Santa Maria Paganica (Figure 4.9d) had the roof of the nave completely collapsed together with its apse. The Cathedral of L'Aquila (Duomo, Figure 4.9e and 4.9f) had the drum almost collapsed and the façade heavily damaged.

Figure 4.11 shows the damages to some monuments in Paganica. Figure 4.11a shows the heavy damage of a masonry wall where security provisions have been constructed. Figures 4.11b, 4.11c and 4.11d show a comparison among different situations for the Concezione church: before the earthquake, just after it and in the phase of safety provision measures. Damages are spread all over the building with local collapse of poor quality masonry. Figure 4.12e shows a tower facing on the Concezione square just before the earthquake in comparison with Figure 4.13f where the same tower exhibits diagonal cracks at 45 degree angle inclination clearly showing a torsional damage mechanism.

(a) safety provisions for a masonry wall

(b) Concezione church before the earthquake
(source: Wikipedia - photo by Fernando Rossi)

(c) Concezione church just after the earthquake

(d) Concezione church during the security provisions

(e) Concezione square before the earthquake
(source: Google StreetView © 2010 Google)

(f) Concezione square after the earthquake

Figure 4.11: Monuments in Paganica

4.2.6 The role of ties

Steel ties have a positive effect on the overall resistance of the building against earthquakes. They increase the global stiffness of the building generating a “rigid-box” behaviour of the structure, thus avoiding local damage concentration. They also prevent the separation and the out-of-plane collapse of the façades and the loss of support of the slabs and the roofs; this also reduces the effective length of compressed walls and therefore increases its out-of-plane stability. Unfortunately, this kind of provisions was present in a minor part of the masonry buildings. Figures 4.12a and 4.12b show two examples of a building with ties (Palazzo Nardis and another palace), located in via dell’Arcivescovado (from Duomo square to the

Prefettura, see Figure 4.10). Figures 4.13a and 4.13b show that ties can increase the safety level both of common building and monuments.

(a) corner steel ties

(b) corner steel ties

Figure 4.12: L'aquila – proper use of steel ties

(a) steel ties in common buildings

(b) corner steel ties in the Matrice church

Figure 4.13: Paganica – proper use of steel ties

4.2.7 The role of good state of conservation

A good state of conservation is essential for making a masonry building able to withstand earthquakes. Some self-explaining examples are shown in Figure 4.14 for L'Aquila and Figure 4.15 for Coppito.

(a) restored wall

(b) Spanish Fortress

Figure 4.14: L'Aquila – well restored buildings

(a) restored house

(b) inserted steel ties

(c) restored house

(d) restored house

Figure 4.15: Coppito - well restored buildings

5. Design codes and building regulations in Italy

5.1 MOST DESTRUCTIVE EARTHQUAKES IN THE RECENT PAST

A comparison between the recent seismic history of Italy and the evolution of Italian design codes shows that earthquakes, and in particular the most destructive ones, have been the boost for emanating more adequate seismic design codes. The recent events are a further proof: three months after the L’Aquila earthquake of 6 April 2009, the new design code NTC (that had remained in a “legislative limbo” for several years) has finally become mandatory.

Regional or national codes have always followed each of the most relevant seismic events in the Italian territory that are listed below:

- Friuli Venezia Giulia, May 1976: M_R = 6.4, 989 deaths, around 45000 homeless
- Irpinia, November 1980: M_R = 6.9, 2914 deaths, 250000 homeless
- Abruzzo-Umbria, May 1984: M_R = 5.4
- Umbria-Marche, September 1997: M_R = 5.7, 11 deaths, 32000 homeless
- San Giuliano di Puglia, October 2002: M_R = 5.4, 30 deaths (27 children inside a school)
- L’Aquila, April 2009: M_R = 6.3, 308 deaths, around 65000 homeless.

An overlook on the chronological evolution of Italian regulation on structures can also be useful to figure out the evolution of the construction systems (use of some particular structural system or construction details). The damage pattern of the buildings after the L’Aquila earthquake allows making an evaluation of the efficacy/inefficacy of commonly-used construction systems in case of (strong) earthquakes. As an example, it is well know that the Umbria earthquake has been very important to identify the inadequacy of some structural retrofitting systems widely utilized in the past (as the replacing of light timber roofs with heavy R/C ones).

5.2 ITALIAN CODES

5.2.1 Italian legislation

Looking at the Italian legislation on the design of structures, it results that some prescriptions come from DM LL.PP. i.e. Decreto del Ministero dei Lavori Pubblici – Decree of the Ministry of Public Works, others from CM LL.PP., i.e. Circolare del Ministero dei Lavori Pubblici – Circular of the Ministry of Public Works, and others from OPCM, i.e. Ordinanza del Presidente del Consiglio dei Ministri – Ordinance of the President of the Council of Ministers. A Circolare usually follows a Decreto and is explicative of what prescribed in it.

The Italian reference law for the design and construction of civil engineering works is the Law n.1086 (05/11/1971). All the Ministerial Decrees and Circulars and also the latest Ordinance that followed refer to it.

In case of particularly destructive events, local authorities (in particular Regions affected by the earthquake) have emanated laws; even if in force only locally and not being compulsory everywhere, those laws have then been adopted by designers in the whole Italian territory.

Three are the main subjects of codes: seismic (and non-seismic) design of new structures, seismic classification of the territory and seismic retrofitting of existing structures.

Referring now only to seismic codes, it is possible to make the following classification, by considering the chronological evolution and the contents (Landolfo, 2005):

- Before the 60s, codes were only prescriptive with the aim of reducing the vulnerability of structures.
- Between the 60s and the 80s, codes focused on the collapse limit state occurring in case of very strong (rare) events. Resistance was evaluated by using the *allowable stress design* method.
- Later on, the *Limit State* method, in which both collapse and damage limit states are taken into account, was introduced.
- Finally, only in the last years, the *performance-based design* method has been introduced: for a specific level of seismic intensity, according to a probabilistic distribution, the structural system is supposed not be damaged more than what expected for an appropriate level of performance.

5.2.2 Codes before the 60s

Royal Decree n.193 (1909), Royal Decree n.431 (1927), Royal Decree n.640 (1935), Law n.1684 (1962). In those prescriptive codes, the seismic action was reproduced by equivalent static forces that were function of the dead loads and of different seismic coefficients C_h and C_v determined according to the territory classification of Italy defined at the beginning of the century. This classification has become more precise with the Royal Decree n.431: the Italian territory was divided into two zones (first and second category of seismicity); coefficients were specified for the two zones.

Regarding design prescriptions, the codes focused mainly on masonry structures: regularity in plan, reduction of the effects of torsion, limit on the height of the structures and box behaviour were prescribed. It is peculiar to mention that already in the "Istruzioni per la ricostruzione di Reggio Calabria - Instructions for the reconstruction of Reggio Calabria" (emanated in 1783, after a strong earthquake), it was prescribed to locate the stairs in the centre of the building, to use iron ties in order to bind the structure and two floors was the maximum height of the building allowed. In the Royal Decree n.640 (1935), this limit became 16 m (four floors) for the first category of seismicity and 20 m (five floors) for the second one.

5.2.3 Codes between the 60s and the 80s

Law n.1086 (05/11/1971) "Norme per la disciplina delle opere di conglomerato cementizio armato, normale e precompresso e a struttura metallica - Rules for reinforced and prestressed concrete works and steel works" (and following Circular LL.PP. n.11951 (14/02/1974) "Rules for normal and prestressed reinforce concrete works, and metallic ones – Instructions"). Law 1086 is the reference law for the design of concrete and steel structures and all the Ministerial Decrees, laws (also Ordinances) that followed are updates of it.

Law 64 02/02/1974 "Provvedimenti per le costruzioni con particolari prescrizioni per le zone sismiche - Measures for structures with particular requirements for structures in seismic zones" (and following "Disposizioni concernenti l'applicazione delle norme tecniche per le costruzioni in zone sismiche – Provisions regarding the application of technical rules for structures in seismic zones") is instead the reference law for the seismic design of structures and the following Decree and Circular concerning the seismicity are evolution of it.

Law 64 focused the attention only on the seismic behaviour of structures in case of strong events (500 years of return period): total collapse of the structures had to be avoided and inhabitants had to be kept safe. No reference to the functionality of structures under less strong events was given.

Law 64 introduced for the first time the seismic micro-zonation, attempting therefore also to account for the local effects of the earthquake. The seismic action could be simulated by means of equivalent static forces or by modal analysis. In particular in the DM "Approvazione delle norme tecniche per le costruzioni in zona sismica – Approval of the technical rules for structures in seismic zones" that followed in 1975, seismic design spectra were introduced; peak ground acceleration in those spectra was smaller than what expected for strong events, because the hysteretic behaviour of the structures was also taken into account.

For the first time, in this code a seismic resistance was required also for masonry buildings and some retrofitting systems were also described. Unfortunately, no (new) specific regulation was produced for masonry structures (and reference ones were still the Decreti Regio of the beginning of the century). The first one would arrive much later, only in 1987!

One of the retrofitting systems prescribed by this decree was the use of pre-stressed ties: pre-stressing had not to exceed 50% of the maximum allowable stress for the steel and the anchoring had to distribute the stress on the masonry. This is worth to mention because, in spite of this prescription, the lack of ties is still one of the most common causes of collapse of old masonry structures (also in the recent seismic events).

Later on, three strong earthquakes occurred and each of them was followed by a new regional or national code on the seismic behaviour of structures. In particular, after the Friuli earthquake in 1976, Regional Law 20/06/1977 n.30 was emanated. It focused mainly on retrofitting criteria after the earthquake.

After the Irpinia earthquake, DM 02/07/1981 "Normativa per la riparazione ed il rafforzamento degli edifici danneggiati dal sisma nelle regioni Basilicata, Campania e Puglia – Rules for the repair and strengthening of buildings damaged by the earthquake in Basilicata, Campania and Puglia regions" was emanated. The code and the following Circular LL.PP. n.21745 (30/07/1981), gave first hints on how to calculate and verify the resistance of masonry to seismic load. Retrofitting systems and measures providing a reduction of seismic effects and an increment of structural resistance were also described.

Ordinance n.230 (05/06/1984) followed the Umbria earthquake of 1984. It focused more on retrofitting systems such as the use of ties, on retrofitting of horizontal systems and on regularity in elevation.

In the years between 1986 and 1989, codes concerning the seismic retrofitting of monumental heritage were emanated. No regulation for those structures was available before. They are: Circular Cultural Heritage n.1032 18/07/1986 "Interventi sul patrimonio monumentale a tipologia specialistica in zone sismiche: raccomandazioni – Interventions on cultural heritage with special typology in seismic zones: recommendations" and National Committee for the Prevention of Cultural Heritage against seismic risk 14/07/1989 "Direttive per la redazione ed esecuzione di progetti di restauro comprendenti interventi di miglioramento anti-sismico e manutenzione nei complessi architettonici di valore storico-artistico in zona sismica – Directives for the drafting and execution of restoration projects comprising interventions for the seismic improvement and for the maintenance of architectural complexes of historical and artistic value in seismic zones". In monumental buildings, the improvement of the seismic behaviour was required; the global behaviour (in particular rigidity) of the structure had not to be changed and only localized retrofitting was possible.

Decree 20/11/1987 "Norme tecniche per la progettazione, esecuzione e collaudo degli edifici in muratura e per il loro consolidamento – Technical rules for the design, execution, testing and retrofitting of masonry structures" and following Circular n.30787 04/01/1989 "Istruzioni in merito alle norme tecniche per la progettazione, esecuzione e collaudo degli edifici in muratura e per il loro consolidamento – Instructions regarding the technical rules for the design, execution, testing and retrofitting of masonry structures". The code considered only the non-seismic loads: the design of masonry structures could be either by means of a simplified method or by using allowable stress design or limit state design. The simplified method, that did not require the calculation and verification of local stresses, was allowed when the structure complied with prescriptions of simplicity and regularity broadly listed in the code itself.

5.2.4 Codes after the 90s

DM 14/02/1992 "Norme tecniche per l'esecuzione delle opere in c.a. normale e precompresso e per le strutture metalliche – Technical rules for the execution of reinforced and prestressed concrete works and steel works": the code dealt with the design of reinforced and precast concrete structures, by focusing only on *allowable stress design*. This code was completely substituted four years later by the DM 09/01/1996.

DM 09/01/1996 "Norme tecniche per il calcolo, l'esecuzione ed il collaudo delle strutture in c.a. normale e precompresso e per le strutture metalliche - Technical rules for the analysis, execution and acceptance tests of reinforced and prestressed concrete structures and of steel structures" and following "Istruzioni per l'applicazione delle Norme tecniche per il calcolo, l'esecuzione ed il collaudo delle opere in cemento armato normale e precompresso e per le strutture metalliche di cui al D.M. 9 gennaio 1996 Instructions on the application of the technical rules for the analysis, execution and acceptance tests of reinforced and prestressed concrete structures and of steel structures": It introduced the use of the *limit states* (but *allowable stress design* is still allowed). The use of ENV Eurocodes 2 and 3 was allowed. The use of smooth bars was still allowed.

Law 61/98 followed the 1997 Umbria-Marche earthquake to regulate the post-event reconstruction phase. D.G.R. Umbria 5180/98 and D.G.R. Marche 2153/98 "Criteri di calcolo per la progettazione degli interventi – Analysis criteria for the design of interventions” are the associated documents emanated by the local authorities to give the technical specifications on the retrofitting methodologies. This document was the first trying to conciliate DM 02/07/1981 (that focused on retrofitting) and DM 20/11/1987 (focused on the design of masonry structures) with DM 09/01/1996 (that for the first time introduced the *limit states*). The parallel approach prescribed foresaw the use of DM 09/01/1996 to estimate the loads and then global and local verifications were to be performed according to the methodologies previously described in DM 02/07/1981 or DM 20/11/1987.

In December 1998 “ Linee guida per progettazione, esecuzione, collaudo di strutture isolate dal sisma” were emanated by Consiglio Superiore dei LL.PP. (Superior Council of public works), giving finally the first regulation on the seismic isolation of structures.

5.2.5 Most recent codes

After the 2002 San Giuliano earthquake, Ordinance Civil Protection O.P.C.M. 3274 was emanated in 2003. The code is inspired by the Eurocodes and tries to tune the European codes (in particular ENV Eurocode 8) with the Italian reality: the prescriptive character of the previous codes was abandoned, while now performance states are clearly defined and analysis and design procedures are defined according to them.

OPCM 3274 never became definitive and above all with a legal status: several updates followed and after the L’Aquila earthquake, it has been substituted by the “Nuove Norme Tecniche per le Costruzioni – New technical rules for structures ” NTC 2008, approved in July 2009.

Table 5.1: Most relevant earthquakes in Italy and Design Codes that followed

EARTHQUAKE	DOCUMENT	YEAR
5 February 1783 – Calabria & Sicilia regions	Instructions for the reconstruction of Reggio Calabria	1783
28 December 1908 – Calabria & Sicilia regions	Royal decree	1909
6 May 1976 – Fruili region	Regional Law 20/06/1977 n.30	1977
23 November 1980 - Irpinia regions	DM “Rules for the repair and strengthening of buildings damaged by the earthquake in Basilicata, Campania and Puglia regions”	1981
29 April 1984 – Umbria region	Ordinance n.230 (05/06/1984)	1984
26-27 September1997 – Umbria & Marche regions	D.G.R. Umbria 5180/98 and D.G.R. Marche 2153/98 “Analysis criteria for the design of interventions”	1998
31 October 2002 – San Giuliano di Puglia	Ordinance Civil Protection O.P.C. 3274	never compulsory
6 April 2009 – L’Aquila	NTC 2008	2009

Please note that Table 5.1 does not report all the codes previously mentioned but only those that immediately followed strong seismic events.

6. Summary and conclusion

The effects of the earthquake of 6 April 2009, although limited to a relatively small area, were devastating: further to the 308 victims, the towns of Onna and Paganica were almost destroyed and most of the buildings in the historical centre of the city of L’Aquila, including several monuments, were very heavily damaged.

The earthquake occurred in an area that has experienced strong earthquakes in the past and that has been classified in the second-highest seismic hazard zone of Italy. Its magnitude was in agreement with the historic seismicity, but the values of peak ground acceleration exceeded those of the current seismic classification. Because of the small epicentral distance, significant vertical components of the motion were recorded.

Old reinforced concrete buildings suffered significant damage, as observed in past earthquakes, while new ones evidently satisfied the no-collapse requirement. Nevertheless, the extent of non-structural damage constituted a further threat to the safety of humans and resulted in high repair costs and long restoration times. This calls for a review of the performance requirements for non-structural elements subjected to strong earthquakes.

Detrimental structural features and conceptual choices of the past, e.g. masonry envelopes, beams only in one direction, irregularities and discontinued vertical elements, were observed also in new reinforced concrete buildings. The enforcement and correct application of design codes will gradually modernise such aspects of the local building tradition.

Regarding new buildings and refurbishment of old ones, owners and users often appear to have a higher appreciation for aesthetics and energy efficiency (in other words, savings on electricity and fuel bills) than for structural safety. These requirements are often in conflict, as in the case of masonry envelopes, and therefore an appropriate balance should be sought by building regulations.

Masonry buildings suffered extensive damages, especially when very poor quality materials coupled with wrong past restoration interventions. On the other side, the presence of steel ties and an overall good state of conservation/restoration had a significant role in reducing the vulnerability of masonry buildings.

Churches resulted very vulnerable to seismic loads and experienced many local or global collapses. Provisional supports are fundamental during the pre-recovering and reconstruction phase in order to avoid further collapses and prevent damages to frescos and artworks.

L’Aquila event has been a strong input for the final updating of the Italian regulations in the matter of seismic design of structures. Previous regulations were first of all not properly classifying the Italian territory, L’Aquila municipally included, and in addition, were not in line with Eurocodes prescriptions. The new NTC represents a first step towards the European regulation.

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European Commission

EUR 24684 EN – Joint Research Centre – Institute for the Protection and Security of the Citizen
Title: The L'Aquila (Italy) earthquake of 6 April 2009: report and analysis from a field mission
Authors: Anna Bosi, Francesco Marazzi, Artur Pinto, Georgios Tsionis.
Luxembourg: Publications Office of the European Union
2011 – 229 pp. – 21 x 29.7 cm
EUR – Scientific and Technical Research series – ISSN 1018-5593
ISBN 978-92-79-18990-6
doi:10.2788/188

Abstract
The province of L'Aquila in central Italy was hit by a 5.8 M_L earthquake in the night of 6 April 2009. The maximum intensity was estimated at 8.5 MCS, evidenced by heavy damage or collapse of many buildings, including heritage ones. 67.500 persons were in need of assistance in the following weeks. This report presents the information collected during a field mission by means of an extensive photographic documentation, focusing on the behaviour of reinforced concrete and masonry buildings. Moreover, the evolution of the building codes in Italy is reviewed.

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LB-NA-24684-EN-C

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ISBN 978-92-79-18990-6

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