



PACIFIC EARTHQUAKE ENGINEERING RESEARCH CENTER

Structural Engineering Reconnaissance of the April 6, 2009, Abruzzo, Italy, Earthquake, and Lessons Learned

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ABSTRACT

In April 2009, a moment magnitude $M_w=6.3$ earthquake struck the central region of Italy near the city of L'Aquila. While the earthquake was tragic — 305 people killed, 1500 injured, and thousands of buildings destroyed — its aftermath provides lessons for earthquake professionals. Within 10 km of the epicenter, the recorded horizontal peak ground acceleration exceeded 0.35g and the ground shaking had high-frequency content with relatively short duration. The damage indicated strong effects of site conditions, where heavy damage occurred to structures founded on young sediments. Old unreinforced masonry buildings made of mortar and multi-wythe rubble-stone or clay bricks were significantly damaged. These buildings were typically two or three stories tall and the damage ranged from wall cracking to severe damage and collapse. Some buildings with retrofitted cross-ties to reduce out-of-plane wall deformation performed reasonably well with limited cracking and no out-of-plane collapses. Reinforced concrete (RC) buildings ranged from two to eight stories tall. The majority of modern RC buildings were designed for horizontal acceleration of about 0.25g. In the epicentral region, little attention was paid to ductility requirements (e.g., smooth reinforcing bars, short lap splices, and insufficient column ties and transverse reinforcement in the beam-column joints were used). The designs appear to have ignored the effect of infill walls and some construction material was of poor quality. Although these deficiencies are serious, the widespread damage most likely resulted from the lack of ductility and the brittleness of exterior infill walls and interior partitions. There were also isolated cases of RC frame damage due to shear failures that led to soft-story mechanisms.

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1 Overview

1.1 INTRODUCTION

On April 6, 2009, at 3:32 a.m. local time, a moment magnitude $M_w=6.3$ earthquake (Fig. 1.1) struck the central region of Italy near the city of L'Aquila, the capital of the Abruzzo region. The earthquake killed 305 people, injured 1500, and destroyed or damaged between 10,000 and 20,000 buildings (EERI 2009). The Abruzzo region is located 80 km east of Rome and has a population of 1,300,000 inhabitants. Most of the damage occurred in the medieval city of L'Aquila, population 73,000, and its surrounding villages. Before 1950, the Abruzzo region in southern Italy was a region of poverty, but since then has had persistent economic growth that was stimulated by the construction of two highways between Rome and the east coast.



Fig. 1.1 Epicenter of L'Aquila earthquake

1.2 ORGANIZATION OF THE REPORT

This report is organized into six chapters including this introductory chapter. Seismic hazard, in terms of ground motion characteristics, is presented in Chapter 2. General damage observations of historical unreinforced masonry (URM) buildings, a hospital, and a bridge are explained in Chapter 3. The damage observed in the special classes of reinforced concrete (RC) buildings and RC frames with URM infill walls are described in detail in Chapter 4. Chapter 5 presents the overall damage in relation to similar recent earthquakes and to the building stock in the San Francisco Bay Area, California. Finally, conclusions and lessons learned are summarized in Chapter 6.

2 Ground Motion Characteristics

The event was located in the Abruzzo region at 42.334°N and 13.334°E coordinates at a focal depth of 8.8 km. The earthquake was related to a normal faulting mechanism with direct movement that extended for 15 km in NW-SE direction, dipping SW, and whose extension to the surface was localized at the fault of Paganica (USGS 2010). The ground motion records of the earthquake have been produced from the stations of the National Accelerometric Network of Italy (INGV 2010). The stations are installed in areas of greater seismic risk throughout Italy. These ground motions are important for the earthquake engineering community, since there are very limited well-recorded normal fault data available worldwide. In the Next Generation Attenuation (PEER NGA) database (Power et al. 2008), 20 out of a total number of 175 earthquakes relate to normal faulting, whereas only 91 stations out of a total of 3551 relate to these earthquakes.

2.1 TIME HISTORIES AND PEAK VALUES

Peak values of the acceleration (PGA), velocity (PGV), and displacement (PGD) for the ground motions of the closest 17 stations to the epicenter are presented in Table 2.1. It can be observed from this table that horizontal PGA values reached up to 0.63g and that some ground motions had vertical PGA as high as the horizontal PGA. It can also be observed that the ground shaking is significantly attenuated for far-fault stations (i.e., epicentral distances greater than 19.3 km in Table 2.1). The locations of the near-fault stations and the epicenter are shown in Figure 2.1. Here it can be observed that the city center of L'Aquila is very close to the epicenter (distance is less than 5 km). In dip-slip events, forward-directivity conditions occur for sites located in the up-dip projection of the fault plane (Bray and Rodriguez-Marek 2004). Since the fault plane is in the NW-SE direction and dipping SW, forward-directivity conditions can be expected in the

near-fault stations (Fig. 2.1). Ground motion traces from the four near-fault stations, namely stations AQA, AQG, AQK, and AQV, are shown in Figures 2.2 and 2.3. High-frequency content of ground accelerations is observed. Apparent velocity pulses due to forward-directivity can be observed in the velocity traces. When the rupture and slip directions relative to a site coincide and a significant portion of the fault ruptures toward the site, the ground motion can exhibit the effect of forward-directivity (Somerville et al. 1997). This effect results in a large pulse of motion (observed in velocity and displacement traces) due to the accumulation of the shear waves traveling ahead of the rupture. It is noted that the maximum PGV from all of the recorded ground motions is 40.5 cm/sec (Table 2.1), which might be considered as moderate intensity. Finally, no “fling” effect in the form of permanent static ground motion displacement is observed in the ground displacement traces.

Table 2.1 PGA, PGV, and PGD values of recorded ground motions

GM Station Label	PGA (g)			PGV (cm/s)			PGD (cm)			R _{RUP} * (km)	R _{JB} ** (km)
	T	L	UP	T	L	UP	T	L	UP		
AQK	0.34	0.34	0.35	30.3	38.5	15.0	7.8	11.8	4.9	4.8	0.0
AQV	0.63	0.60	0.42	36.7	40.5	13.4	8.4	4.1	2.5	6.2	1.8
AQA	0.39	0.45	0.38	30.5	24.5	9.4	6.4	3.9	1.9	6.5	2.0
AQG	0.42	0.43	0.22	33.6	35.9	9.1	7.9	3.9	1.9	6.7	1.9
GSA	0.15	0.15	0.11	9.7	7.4	5.5	3.0	2.2	1.5	7.3	7.2
GSG	0.02	0.03	0.02	3.5	3.1	3.0	1.6	1.8	1.8	12.1	12.1
CLN	0.08	0.09	0.04	4.6	6.7	5.7	2.6	1.9	1.9	21.2	17.6
MTR	0.04	0.06	0.02	3.3	3.1	3.2	1.0	0.7	0.8	23.8	20.7
FMG	0.02	0.03	0.02	2.5	2.8	1.5	1.2	0.6	0.4	23.9	20.8
ANT	0.02	0.03	0.01	1.9	5.4	1.1	0.4	0.5	0.2	25.9	23.1
AVZ	0.06	0.07	0.03	10.5	10.6	3.6	4.6	4.4	1.3	26.4	23.7
CSO	0.02	0.02	0.02	2.2	3.1	2.0	1.0	0.6	0.7	36.8	34.8
ORC	0.07	0.04	0.03	6.1	3.7	3.8	1.3	0.9	0.6	38.4	38.4
SUL	0.03	0.03	0.02	2.7	2.8	2.1	0.8	1.1	1.0	39.6	39.6
CHT	0.03	0.03	0.02	6.4	5.4	3.6	2.9	2.6	1.7	51.4	51.4
CDS	0.01	0.01	0.01	2.4	2.2	1.8	0.8	1.0	0.9	73.6	73.6
BOJ	0.01	0.01	0.01	3.5	1.7	1.4	1.0	0.8	0.5	119.1	119.1

*The shortest distance between the recording site and the rupture plane of earthquakes

**The Joyner and Boore (1981) distance, a measure of how far the site is from being over the hanging wall

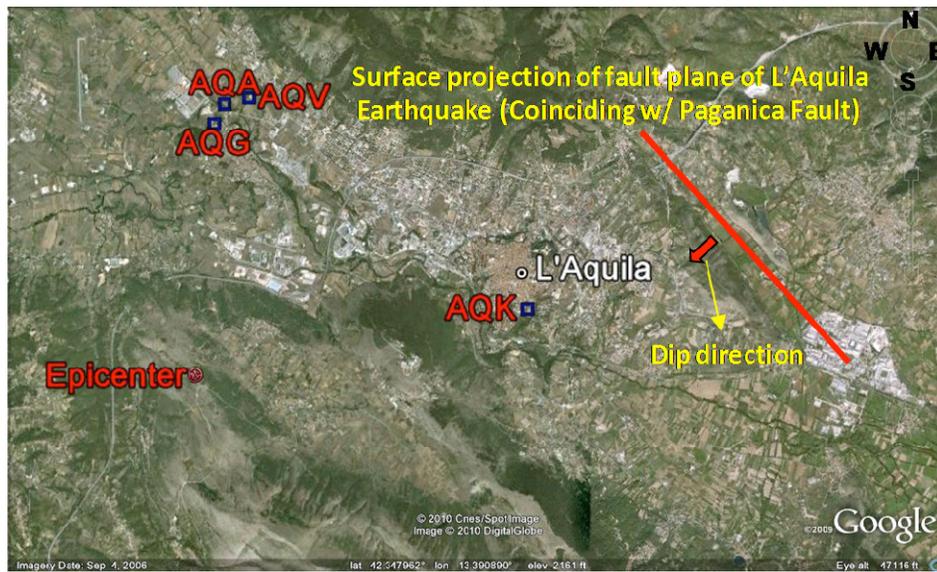


Fig. 2.1 Locations of near-fault stations, epicenter, and fault

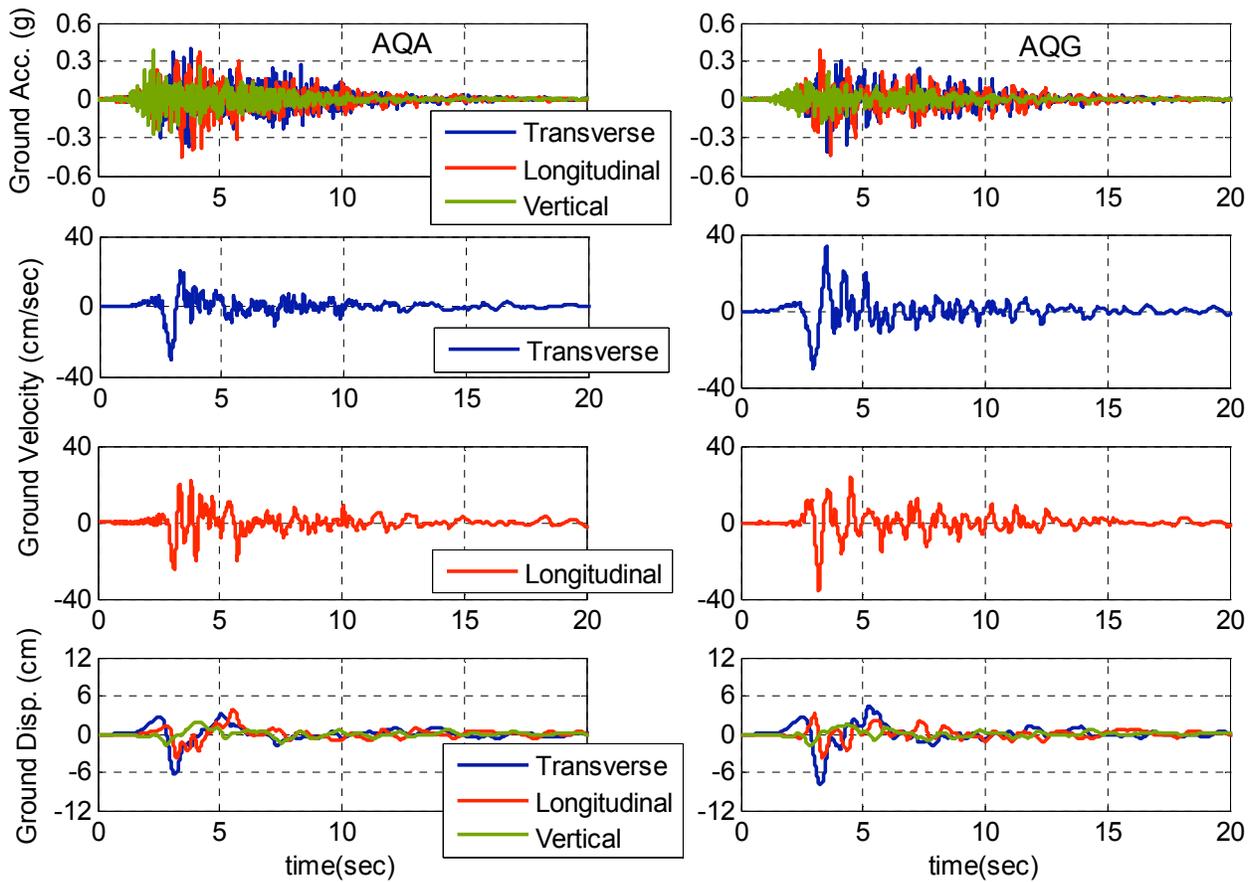


Fig. 2.2 Ground motion traces at near-fault stations AQA and AQG

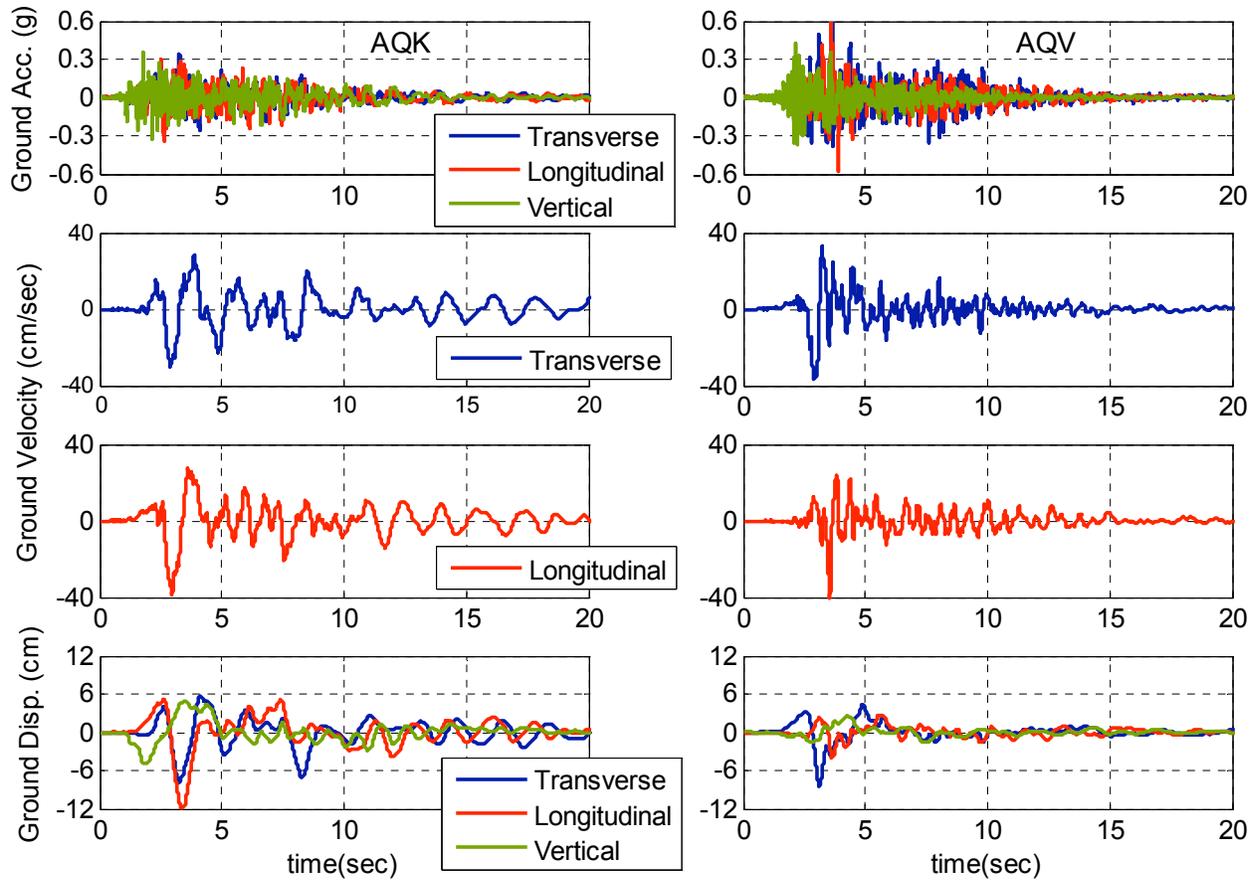


Fig. 2.3 Ground motion traces at near-fault stations AQK and AQV

2.2 SPECTRA

Pseudo-acceleration spectra (PSa) of the near-fault ground motions are presented in Figure 2.4. It is observed that PSa values greater than $1.2g$ are present for periods between 0.1 and 0.5 sec for the horizontal components. Moreover, PSa of the vertical component is smaller than that of the horizontal components in the whole period range for the ground motions with greater horizontal PGA. For one of the ground motions with similar horizontal and vertical PGA, the one labeled AQA, of Eurocode ground type B, PSa of the vertical component is still smaller than that of the horizontal components in the whole period range. For the other ground motion with similar horizontal and vertical PGA, the one labeled AQK, of Eurocode ground type C, PSa of the vertical component is similar to that of the horizontal components for periods smaller than 1.0 sec. For greater periods, PSa of the vertical component is smaller than that of the horizontal components, since the vertical component generally contains higher frequencies.

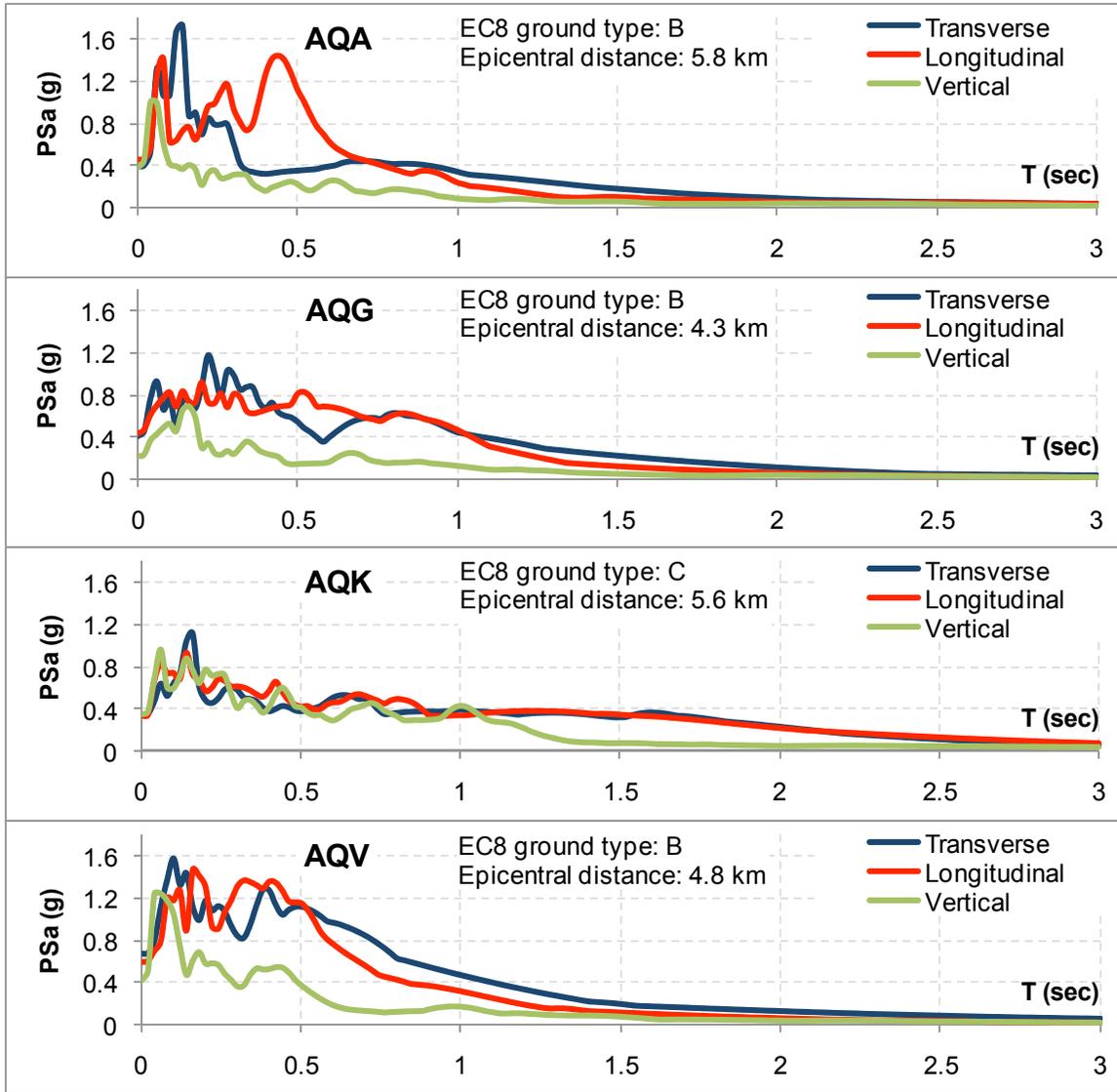


Fig. 2.4 Pseudo-acceleration spectra of near-fault ground motions

2.3 COMPARISON WITH EUROCODE SPECTRA

PSa of the recorded ground motions are compared in Figure 2.5 with the Eurocode Type 1 spectra, which is the spectra type recommended for earthquakes with surface-wave magnitude (M_s) greater than 5.5. The horizontal response spectrum is defined with Equation 2.1 and Table 2.1; the vertical response spectrum is defined with Equation 2.2.

The Eurocode spectra are plotted using the PGA of the recorded ground motions. It can be observed that the Eurocode PSa for horizontal components is greater than that of the recorded ground motion for periods greater than 1.0 sec for the ground motions of ground type B. The

match of the PSa values for periods greater than 1.0 sec is quite good for the ground motion of ground type C (labeled AQK). Except the AQA ground motion, the recorded ground motion spectra have a peak at about 0.15~0.2 sec and after this point PSa suddenly drops and becomes much lower than the Eurocode spectra values. Recorded vertical ground motion and the corresponding Eurocode spectra values match quite well for longer periods (greater than 1.0 sec), and these values are also similar for periods smaller than 1.0 sec except for the AQA ground motion.

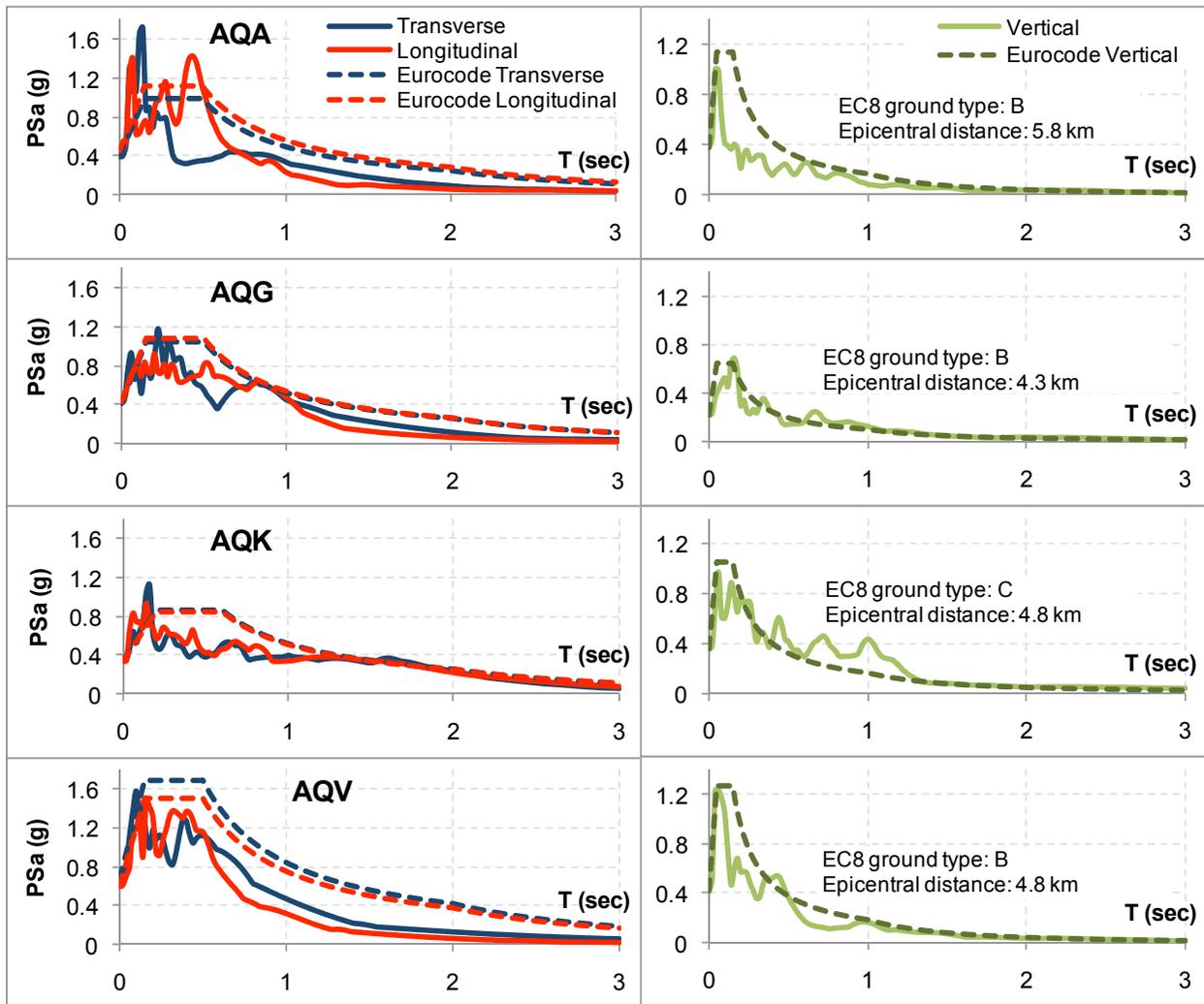


Fig. 2.5 Comparison of recorded ground motion spectra with Eurocode Type 1 spectra

$$S_h(T) = a_g \cdot S \cdot \left[1 + \frac{T}{T_B} \cdot (\eta \cdot 2.5 - 1) \right] \quad 0 \leq T \leq T_B \quad (2.1a)$$

$$S_h(T) = a_g \cdot S \cdot \eta \cdot 2.5 \quad T_B \leq T \leq T_C \quad (2.1b)$$

$$S_h(T) = a_g \cdot S \cdot \eta \cdot 2.5 \cdot \left(\frac{T_C}{T} \right) \quad T_C \leq T \leq T_D \quad (2.1c)$$

$$S_h(T) = a_g \cdot S \cdot \eta \cdot 2.5 \cdot \left(\frac{T_C T_D}{T^2} \right) \quad T_D \leq T \leq 4 \text{sec} \quad (2.1d)$$

where $S_h(T)$ is the horizontal spectral acceleration corresponding to period T ; a_g is the design ground acceleration on ground type A taken as the PGA of the recorded ground motions (reported in Table 2.1) in order to compare the shapes of the spectra; S is the soil factor (Table 2.2) considered as unity, since PGA of the recorded ground motions is used for a_g , and η is the damping correction factor with a reference value of $\eta = 1$ for 5% viscous damping. The recommended values in Eurocode for the periods that separate the different parts of the spectra, mainly T_B , T_C , and T_D , are given in Table 2.2.

Table 2.2 Values of parameters in Eurocode Type 1 elastic horizontal response spectra

Ground Type	S	T_B (sec)	T_C (sec)	T_D (sec)
A	1.00	0.15	0.40	2.00
B	1.20	0.15	0.50	2.00
C	1.15	0.20	0.60	2.00
D	1.35	0.20	0.80	2.00
E	1.40	0.15	0.50	2.00

$$S_v(T) = a_{vg} \cdot \left[1 + \frac{T}{T_B} \cdot (\eta \cdot 3.0 - 1) \right] \quad 0 \leq T \leq T_B \quad (2.2a)$$

$$S_v(T) = a_{vg} \cdot \eta \cdot 3.0 \quad T_B \leq T \leq T_C \quad (2.2b)$$

$$S_v(T) = a_{vg} \cdot \eta \cdot 3.0 \cdot \left(\frac{T_C}{T} \right) \quad T_C \leq T \leq T_D \quad (2.2c)$$

$$S_v(T) = a_{vg} \cdot \eta \cdot 3.0 \cdot \left(\frac{T_C T_D}{T^2} \right) \quad T_D \leq T \leq 4 \text{ sec} \quad (2.2d)$$

where a_{vg} is recommended to be 0.9 of a_g and 0.05, 0.15, and 1.0 sec are recommended for T_B , T_C , and T_D , respectively, for Type 1 spectra. Similar to the horizontal ground motions, a_{vg} is taken as the PGA of the vertical components of the recorded ground motions.

2.4 COMPARISON WITH NGA PREDICTIONS

Five sets of ground motion models were developed as a result of the Next Generation Attenuation (NGA) project. The objective of this project was to develop new ground motion prediction relationships (attenuation models) for shallow crustal earthquakes in the western United States and similar active tectonic regions (Power et al. 2008). As mentioned previously, there are very limited well-recorded normal fault data available worldwide. Hence, the ground motion records of the L'Aquila earthquake provide a good opportunity for comparison with the NGA predictions.

Boore-Atkinson (2008) and Campbell-Bozorgnia (2008) attenuation models are employed as the prediction equations with equal weights. Distance measures used in the equations, namely, R_{RUP} , which is defined as the closest distance to the rupture plane, and R_{JB} , which is defined as the closest distance to the surface projection of the rupture plane, are calculated by using the coordinates and the depth values of the vertices of the rupture plane presented in Table 2.3 (Chioccarelli and Iervolino 2010). In the calculations, the distance between each degree of latitude is accepted to be 111 km and the distance between each degree of longitude is accepted to be 85 km. Calculated R_{RUP} and R_{JB} values are shown in Table 2.1.

Table 2.3 Coordinates of rupture plane vertices

	Vertex 1	Vertex 2	Vertex 3	Vertex 4
Longitude	13.424	13.552	13.465	13.336
Latitude	42.405	42.293	42.238	42.351
Depth (km)	0.6	0.6	11.8	11.8

The ground motion parameters in the NGA prediction models are not calculated using the traditional geometric mean of the two recorded horizontal components. Instead, a new geometric mean is utilized, referred to as “GMRotI50” by Boore et al. (2006), which is independent of both accelerometer orientation and oscillator period, and leads to a more robust horizontal ground motion component. In this new definition, ground motion parameters including PGA, PGV, and spectral acceleration are calculated considering all the possible rotated acceleration histories. For this reason, PGA, PGV and spectral acceleration for the recorded ground motions of L’Aquila earthquake are also calculated not as the geometric mean, but as “GMRotI50” Comparisons of recorded and median predicted PGA and PGV are shown in Figure 2.6. It can be observed that PGA predictions are overestimated for smaller PGA values consistent with the previously stated observation that the attenuation in the ground shaking is significantly attenuated for far-fault stations. Underestimation of PGA and PGV for near-fault ground motions may be due to the lack of forward-directivity effects in the equations. Considering that the predictions are median predictions in Figure 2.6, and considering the median \pm one standard deviation (σ) values (Fig. 2.7), it can be stated that the predictions are good within a certain range as discussed below.

Figures 2.8 and 2.9 show the residuals of PGA and PGV from the recorded ground motions relative to the NGA predictions plotted against the Joyner and Boore distance, R_{JB} . The residual for an intensity parameter is defined as “ \ln (recorded) - \ln (prediction from NGA).” The R_{JB} value of station AQQ, which is equal to zero, is plotted as $R_{JB} = 1$ km in these figures. The results shown in Figure 2.8 are consistent with the observations stated for Figure 2.6. It can be observed that PGA predictions are overestimated for distances greater than 10 km, indicating that the actual distance attenuation is faster than that predicted by the NGA models. PGA and PGV values are underestimated for near-fault distances, which might be due to the lack of consideration of forward-directivity effects in the equations. Figures 2.8 and 2.9 give the additional information that the residuals in PGV predictions are smaller than those in PGA predictions.

Median and median $\pm \sigma$ NGA response spectra are plotted, together with the response spectra of recorded ground motions in Figure 2.10. Five hundred periods between 0.02 and 10 sec are used for the determination of the rotation angle θ_{min} . However, the spectra in Figure 2.10 are calculated for 21 periods for which the coefficients are available for the NGA prediction

equations. Except for the low periods (smaller than 0.1 sec), the spectral acceleration of the recorded motions are generally in between the median $\pm \sigma$ predictions.

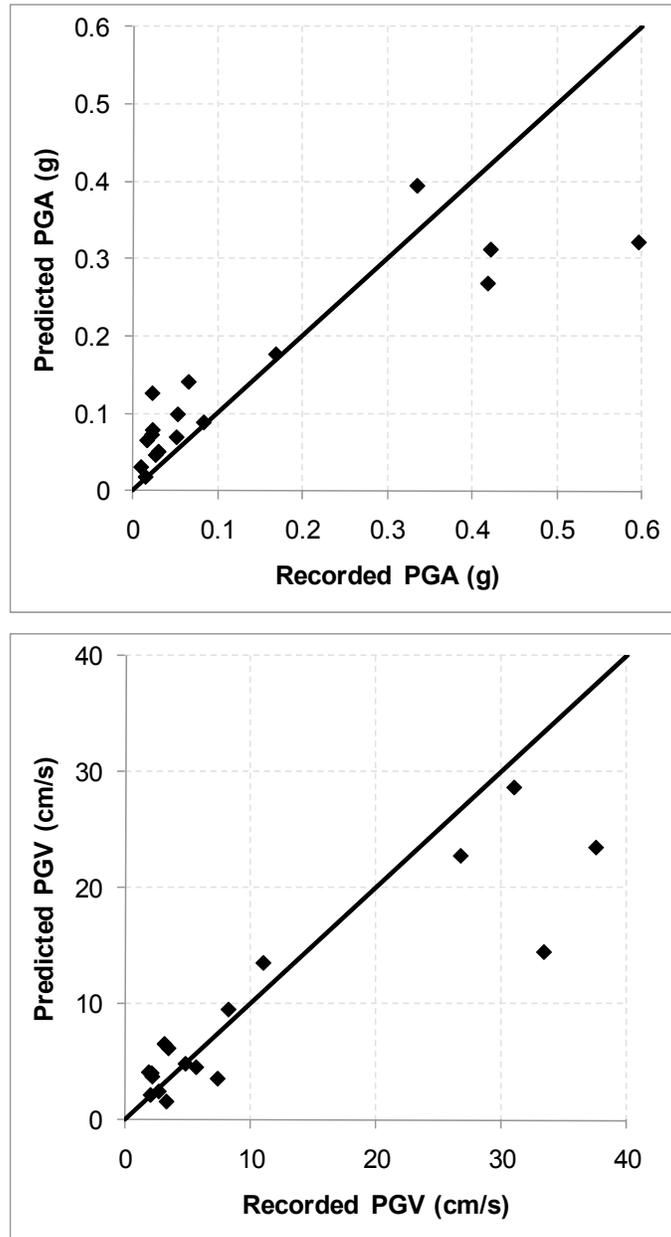


Fig. 2.6 Comparison of recorded and predicted ground motion median peak values

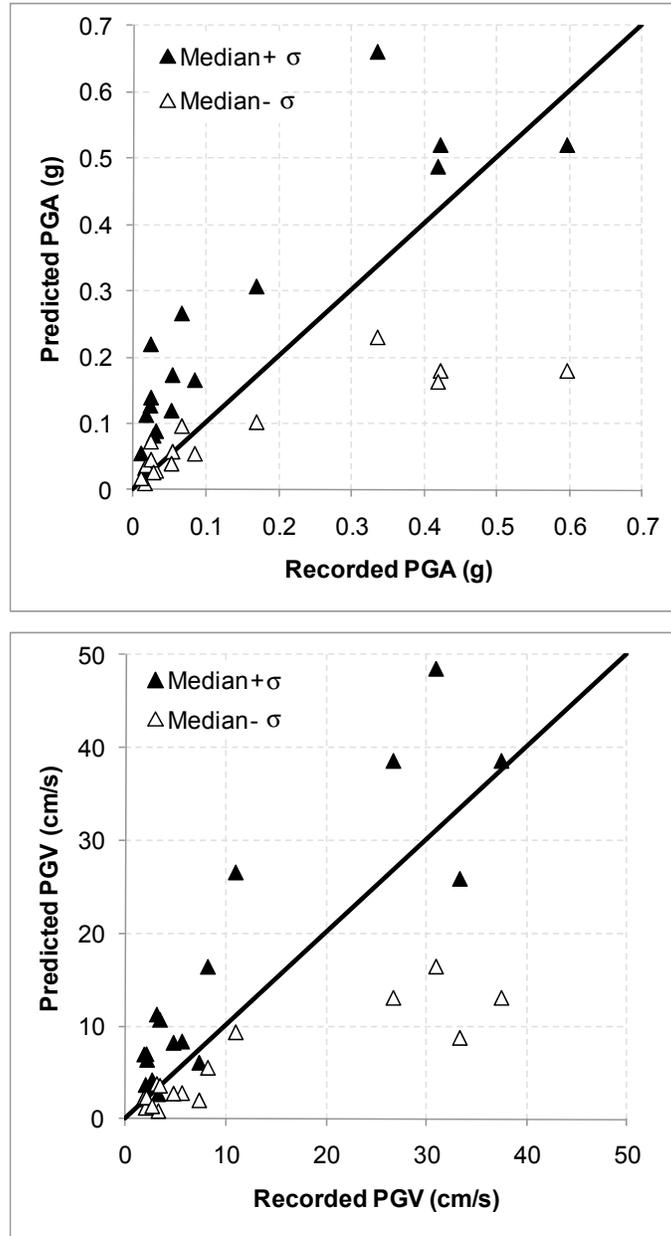


Fig. 2.7 Comparison of recorded and predicted ground motion (median $\pm\sigma$) peak values

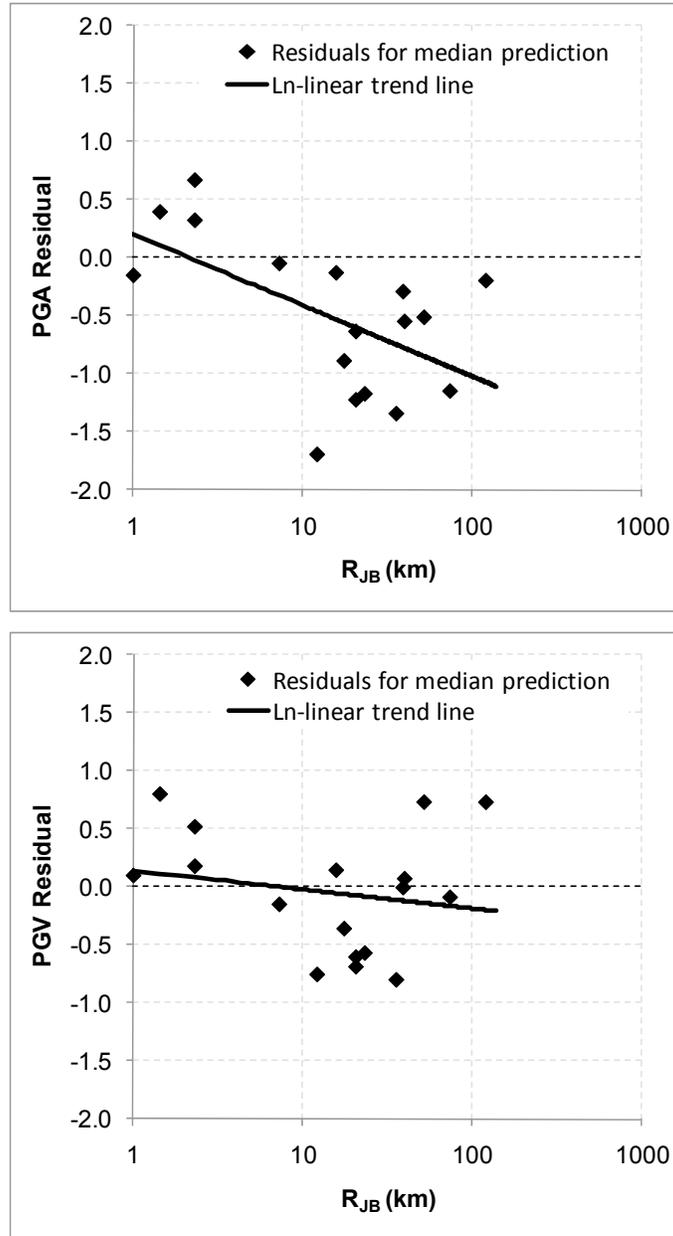


Fig. 2.8 Residuals of PGA and PGV from recorded ground motions relative to NGA median predictions

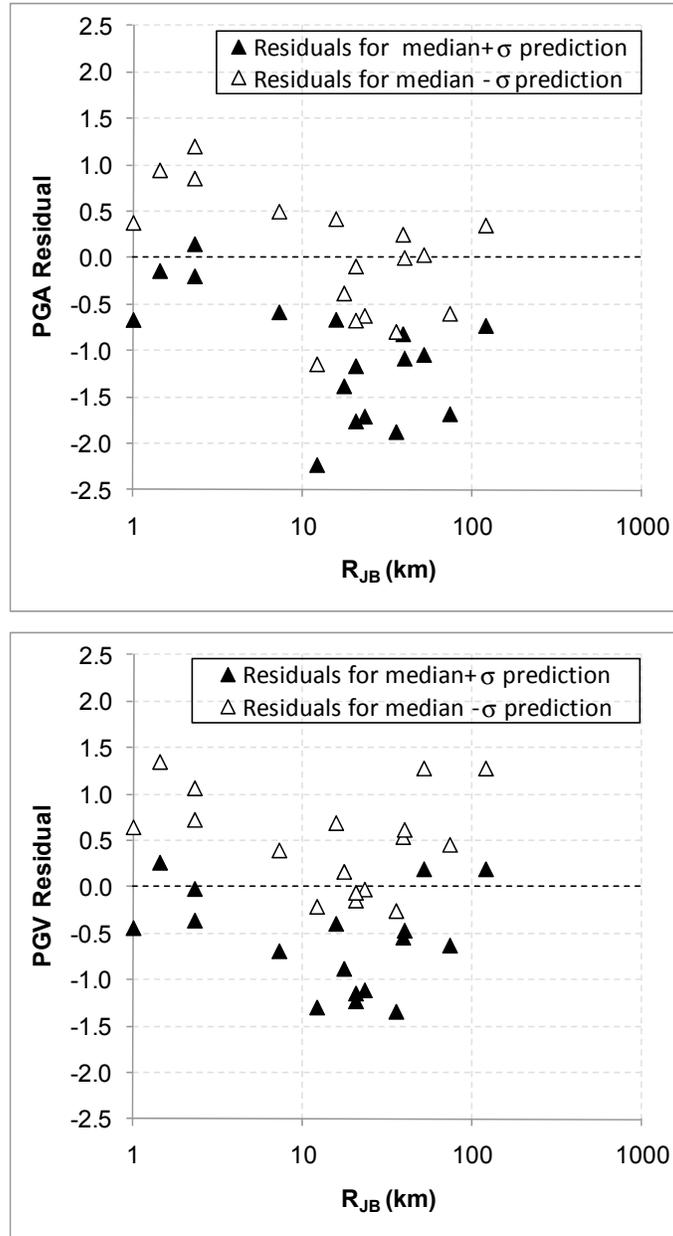


Fig. 2.9 Residuals of PGA and PGV from recorded ground motions relative to NGA median $\pm\sigma$ predictions

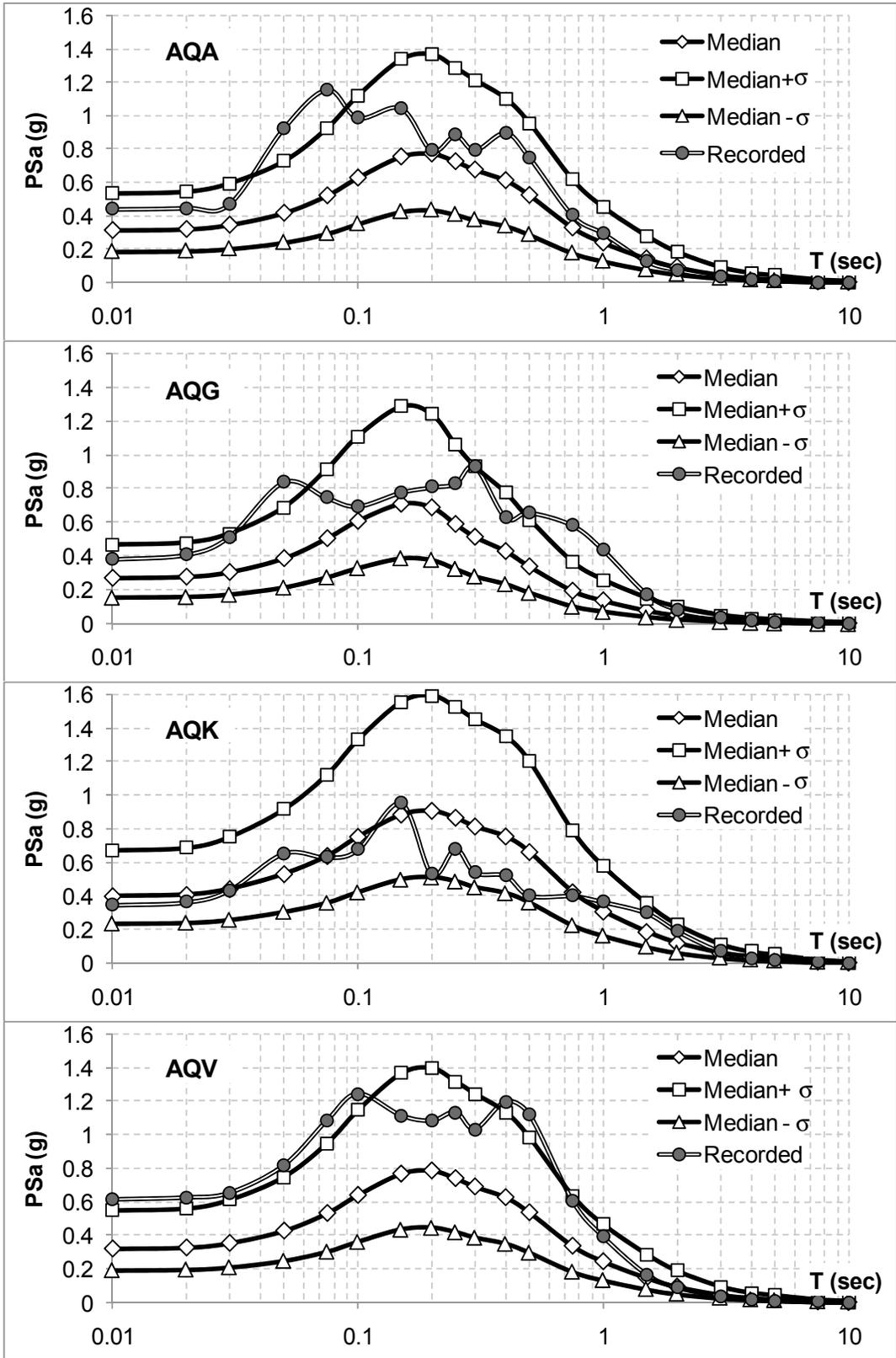


Fig. 2.10 Comparison of recorded and predicted ground motion response spectra

3 General Damage Observations

This chapter summarizes the damage observed in the historical unreinforced masonry (URM) buildings, a hospital, and a bridge. The damage observed in the special classes of reinforced concrete (RC) buildings and RC frames with URM infill walls are discussed in more detail in Chapter 4.

3.1 HISTORICAL URM BUILDINGS

The Abruzzo region has many historic buildings, which date to the 13th century and represent between 20% and 50% of the total number of buildings. The historical buildings of L'Aquila and its surroundings are typically two or three stories tall and built with URM made of mortar and multi-wythe rubble-stone or clay bricks. Earthquake damage experienced by these buildings ranged from wall cracking to severe damage and collapse.

Damage to the historical buildings can be attributed to the Italian cultural preservation philosophy, which is of such importance that historic structures are most often rebuilt in the same manner and with similar materials as the original construction. In addition, people who choose to live and work in these buildings understand and accept the risk (Degenkolb Engineers 2010). In recent years (starting from 2005), this philosophy has started to change. Although conservation of both the materials and the functionality are still the main objectives, the intervention process is significantly enhanced by defining knowledge levels and introducing new procedures of analysis and assessment and new criteria for the intervention on existing structures (Modena et al. 2009). In the recent Italian code (NTC 2008), several common intervention techniques have been explained that aim at improving structural connections, reducing horizontal diaphragm flexibility, increasing masonry strength, and performing interventions on vaults, arches, and pillars (Modena et al. 2009).

The greatest damage to historic buildings was observed in small towns located east of L'Aquila, where the complete collapse of several buildings was evident. Figure 3.1a shows an old URM building completely destroyed in the town of Onna, and Figure 3.1b shows another in the same town with the second story totally collapsed. Figure 3.1c shows a house with a damaged wall that did not fail. It is observed that this wall was constructed with mixed masonry materials of bricks (above the window opening) and rubble-stone (to the right of the window opening), clearly showing low-quality construction. The area constructed with rubble-stone showed more damage than the brick area, as shown in Figure 3.1c. In Figure 3.1d, a masonry wall is shown that failed due to poor quality of masonry and possibly poor connection of the roof to the wall. Figure 3.1e shows a flexural wall failure due to the change in story stiffness and the inadequate connection between the wall and the middle floor. Figure 3.1f shows a partially collapsed building. The disintegration of the masonry units in the standing portion of the building suggests that the collapse of the other part took place due to the failure of the walls as a result of disintegration of masonry material. The locations of the discussed buildings are shown with red squares in Figure 3.1g.

In the Italian historic city centers, “aggregated” masonry buildings, which consist of conglomerations or blocks of masonry buildings with very close spacing, if any, are common. These buildings are the result of the progressive growth of the urban tissue, under which elevations are added to existing buildings and enlargements are made to plans by adding structural units in contact with previously existing ones, so that adjacent units generally share the same boundary wall (Magenes and Penna 2009). Pounding is one of the structural problems of these aggregated masonry buildings, especially in the cases of adjacent units of different heights and floors at different elevations (Borri and De Maria 2009). Total collapse, partial collapse, and heavy damage of the aggregated masonry buildings are shown in Figure 3.2. It is probable that if these units were standing alone, the damage they experienced would have been less. It is worth mentioning that site amplification on soil deposits also played an important role in the observed heavy damage (GEER 2009).



(a) Destroyed old URM building



(b) Second-story damage



(c) Wall damage in an old URM house



(d) Out-of-plane masonry wall failure



(e) Flexural damage in masonry wall



(f) Disintegration of masonry material



(g) Locations of the above-damaged buildings

Fig. 3.1 Damage in URM buildings in Onna



(a) Partially collapsed aggregated buildings



(b) Partial and total collapse of aggregated buildings



(c) Same boundary wall

(d) Partial collapse

Fig. 3.2 Partial and total collapse of aggregated buildings in Onna

The historic buildings of the city of L’Aquila, in general, performed better than those of nearby towns. The better performance can be attributed to L’Aquila’s having richer people who were able to afford better quality of material and construction (EERI 2009). Figure 3.3a shows an out-of-plane mode of failure at the third floor of a building in L’Aquila. Figure 3.3b shows damage to the historic church Santa Maria del Suffragio, which lost its dome. As shown in Figures 3.3c–d, some URM buildings suffered only minor damage and no out-of-plane failure because of the use of cross-ties that reduced this type of wall deformation (Mosalam 2009a). Similarly, an example of arch strengthening using tie-rods to compensate for the thrust induced

on the bearing walls (Oliveira and Lourenço 2004) is shown in Figure 3.3e. The locations of the discussed historical buildings are marked with red squares in Figure 3.3f.



(a) Out-of-plane failure



(b) Lost dome of Santa Maria del Suffragio



(c) Cross-ties used for out-of-plane restraint



(d) Anchorage of cross-ties



(e) Tie-rods for arch strengthening



(f) Locations of the buildings

Fig. 3.3 Historical buildings in L'Aquila

Aggregated buildings in L'Aquila were not as heavily damaged as those in Onna, as shown in Figure 3.4a, which can be attributed to better construction quality, and similar number of stories and vertical locations of the floor levels of the adjacent buildings. Damage increased for adjacent buildings with different heights, as shown in Figure 3.4b. The buildings at the edges of these aggregated buildings are most vulnerable because they are subjected to additional lateral

forces from only one side and are not restrained on the other. Figure 3.4c shows the partial collapse of such a building in L'Aquila.



(a) Minor damage in aggregated buildings



(b) Damage in aggregated buildings as a result of different heights of adjacent buildings



(c) Partial collapse of a building at the edge of aggregated buildings

Fig. 3.4 Aggregated buildings in L'Aquila

3.2 SAN SALVATORE HOSPITAL

San Salvatore Hospital, located in Coppito, adjacent to L'Aquila was moderately damaged during the earthquake. It was immediately evacuated after the earthquake while ambulances were arriving with injured people. The construction of this hospital started in 1972 and ended in 2000 (EERI 2009). The hospital is a RC structure with URM infill walls in some regions. Damage was observed both in the structural and non-structural elements. Figure 3.5a shows a shear failure in a column due to insufficient shear reinforcement. Figure 3.5b shows another column that was subjected to flexural damage. Examples of non-structural damage are to a mechanical door (Fig. 3.5c) and to light fixtures (Fig. 3.5d). Damage was observed in a stainless steel pipe connection due to impact (Fig. 3.5e). Sliding of a storage tank about 5 cm relative to the support was observed as shown in Figure 3.5f. The location of the hospital is shown in Figure 3.5g.

The functionality of hospital buildings and healthcare facilities is of vital importance for emergency response after an earthquake. Observed structural and non-structural damage and the evacuation of the hospital immediately after the earthquake is an indication of the fact that traditional earthquake design philosophy based on preventing structural and non-structural elements of buildings from any damage in low-intensity earthquakes, limiting damage in structural and non-structural elements to repairable levels in medium-intensity earthquakes, and preventing the overall or partial collapse of buildings in high-intensity earthquakes, is not suitable for hospitals and similar essential structures. These structures should be designed by following performance-based design principles. Innovative technologies, such as seismic isolation, supplemental damping and the like, should be promoted to enhance the seismic performance of such essential structures (Dolce and Manfredi 2009).



(a) Shear failure in column due to insufficient shear reinforcement



(b) Flexural failure in column



(c) Interior damage of mechanical doors



(d) Interior damage of light fixtures



(e) Pipe damage



(f) Sliding of equipment



(g) Location of San Salvatore Hospital

Fig. 3.5 Damage in San Salvatore Hospital, Coppito

3.3 BRIDGES

The investigation of the seismic vulnerability of the transportation infrastructure has recently gained momentum in Italy. For this purpose, a research project leading to guidelines for the seismic assessment and retrofit of existing bridges has recently been finalized (Pinto and Manchini 2009).

The two main highways of the Abruzzo region are designated as A24 and A25, which connect Rome to the eastern cities of Teramo and Pescara, respectively. Both highways were closed for inspections after the earthquake and were reopened to passenger vehicles a few days later. Minor damage was observed in these highways, where relative displacements of simply supported concrete beams with respect to the bearings were observed. In a secondary road at the south of Onna, significant damage was observed in a RC bridge. Cracks in one of the RC columns, which are attributed to liquefaction of the soil, are shown in Figure 3.6a. Additionally, soil sliding and failure near one of the abutments caused damage (Fig. 3.6b).



(a) Damage in a RC pier



(b) Damage in an abutment due to soil failure

Fig. 3.6 Damage in RC bridge in a secondary road

4 Response of Reinforced Concrete Buildings and Frames with Infill Walls

For design purposes, L'Aquila province was considered to be subject to seismic hazard from 1915, after the Avezzano earthquake. A modern seismic Italian code was published in 1977 and revised in 1999. This code specified a horizontal ground acceleration of 0.23g for L'Aquila province, which results, after the application of reduction factors, in a design base shear of 7% of the building weight for low- to medium-rise buildings (i.e., buildings with fundamental periods between 0.15 and 0.6 sec located on stiff soils). In 2003, a new seismic code was published that increased the horizontal ground acceleration to 0.25g in L'Aquila province and included strict detailed guidelines for ductility. However, only a few buildings have been designed after the 2003 seismic code. In 2008, the seismic code was updated further. In addition, the use of the Eurocode or a technically equivalent design is mandatory (European Commission 2010).

4.1 REINFORCED CONCRETE BUILDINGS WITH INFILL WALLS

After World War II, most residential buildings were built using RC with URM infill walls. These buildings are typically two to four stories tall, but in some cases are up to eight stories. Similar to the Abruzzo region, RC frames containing URM infill walls are a commonly used structural system worldwide. It is recognized that many buildings of this type have performed poorly during earthquakes, e.g., 2001 Bhuj, India; 2005 Kashmir, Pakistan; 2008 Wenchuan, China; and recently 2009 L'Aquila, Italy (Mosalam 2009b).

The damage observed in RC frames with URM infill walls varied from small cracking to severe damage and collapse. Most of the buildings survived but a few collapsed. A representative five-story RC residential building with URM infill walls is shown in Figure 4.1a. This building was located in Coppito, 4 km north-west of L'Aquila, and suffered minor damage. Figure 4.1b

shows cracking at the exterior wall-frame interface in the first story. Figure 4.1c shows diagonal cracks in one of the walls of San Salvatore Hospital between its windows. Figure 4.1d shows moderate damage in the façade of a building located in L'Aquila. Figures 4.1e–f show diagonal cracking in URM infill walls. The locations of these buildings are marked with red squares in Figure 4.1g.

Figure 4.2 shows infill wall failure at the first story of a building, which is typically observed in low- to medium-rise RC frames with stiff URM infill walls, since the first-story URM infill walls experience the largest shear forces. In fact, there is another story under the first story as shown in Figure 4.2c. However, since this story is fixed to the ground near the sidewalk, the building can be considered as a two-story building with infill wall failures at the first story. It is observed that the first-story frame members were not damaged except for some minor cracking in the beams that may have taken place after the first story became a soft story with the failure of the infill walls. The damage-free situation in the frame members can be attributed to two reasons. First, the interior infill walls were not damaged, as shown in Figure 4.2d, providing stiffness and strength to the first story. Second, the duration of shaking was short. The effective duration, i.e., time interval between 5% and 95% of the integral of the square of acceleration during the ground motion (Trifunac and Brady 1975), is between 6.5 and 8.5 sec for stations AQA, AQG, and AQV and between 11.0 and 12.0 sec for station AQK, the station closest to the building. Because of this short effective duration, infill walls played a protective role, dissipating energy through damage during the effective duration. Moreover, the frame members did not experience significant damage after the first story became a soft story, since the ground motion lost intensity. Another building with similar damage situation is shown in Figure 4.2e. In Figure 4.2f the locations of these buildings are marked with red squares and the closest station AQK is marked with a blue square.

Other examples of damaged infill walls that protected the frame members from damage are shown in Figure 4.3. Infill wall separation from the frame at the interface and corner crushing leading to possible out-of-plane failure are shown in Figures 4.3a–b. It is noted that the infill walls consisted of double-layer hollow blocks typical of Italian building practices. Figure 4.3c–d show infill damage in the form of diagonal cracking for the buildings identified in Figure 4.3e. Although the infill walls protected the frame members from damage, it should be mentioned that the damage in URM infill walls is hazardous. Therefore, such walls should be used with care and properly considered in the design (Mosalam 2009a).



(a) RC residential building with URM infill wall



(b) Cracking between RC frame and URM infill



(c) Shear cracks between windows



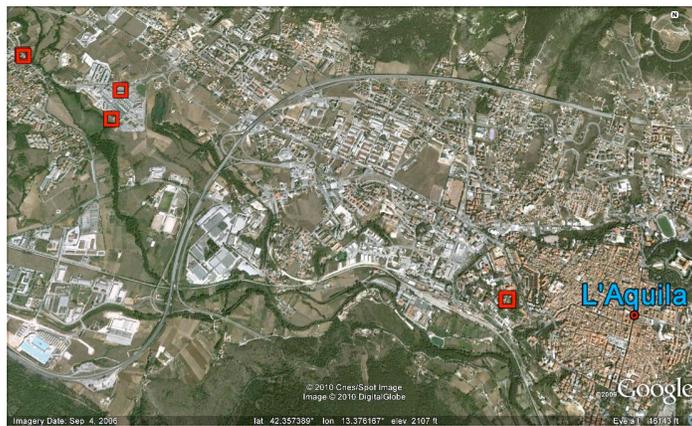
(d) Moderate damage in a building façade



(e) Diagonal crack in infill wall near a window



(f) Diagonal crack in first-story infill wall



(g) Locations of the buildings shown in the above photographs

Fig. 4.1 Minor to moderate damage in RC frame buildings with URM infill walls



(a) Building with infill wall failure (view 1)



(b) Building with infill wall failure (view 2)



(c) Fixed story below the first story



(d) Undamaged interior infill walls



(e) Another building with infill wall failure



(f) Locations of the buildings

Fig. 4.2 Buildings in L’Aquila with first-story infill wall failures

4.2 EFFECT OF SEISMIC DETAILS IN REINFORCED CONCRETE FRAMES

In the earthquake region, RC buildings that suffered from severe damage to collapse generally had poor seismic detailing and were founded on soils of young sediments. Figure 4.4a shows beam-column joint damage due to lack of transverse reinforcement in the joint region. Examples of short-column damage are shown Figures 4.4b–c for buildings identified in Figure 4.4d.



(a) Infill wall-frame separation and corner crushing of the infill wall



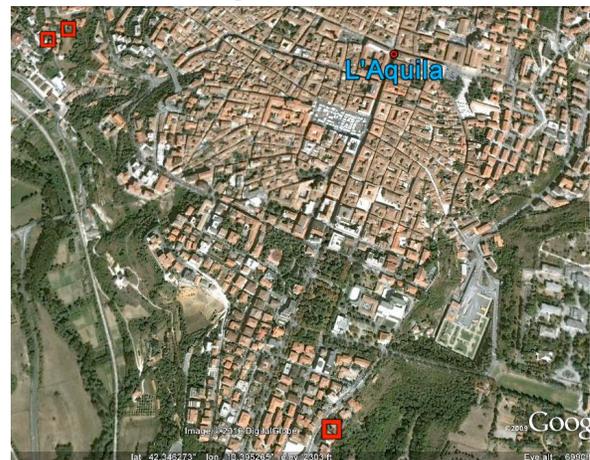
(b) Out-of-plane failure and corner crushing of the infill wall



(c) Infill wall-frame separation and diagonal cracking in the infill wall



(d) Diagonal crack failure of the infill wall

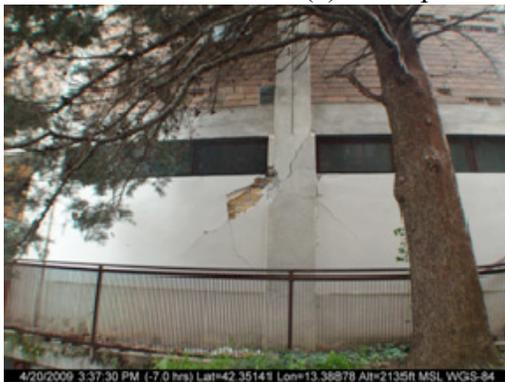


(e) Locations of the buildings

Fig. 4.3 Examples of damage in infill walls with undamaged frame members



(a) Examples of beam-column joint damage



(b) Diagonal cracking in short columns



(c) Cover spalling in a short column

(d) Locations of the buildings

Fig. 4.4 Examples of RC beam-column joint and short-column damage

4.3 NON-DUCTILE RC FRAME/URM INFILL WALL INTERACTION

Figure 4.5a shows two similar, closely spaced buildings located in L'Aquila. Although it seems that the buildings suffered similar damage at first sight (walls at the same stories and same bays failed), closer inspection of the building to the right (Fig. 4.5c) reveals significant damage at the third-story beam-column joints and columns, while this is not the case for the building to the left (Fig. 4.5b). This may be attributed to differences in the orientation of the buildings with respect to the earthquake shaking. Moreover, better reinforcement detailing of the building in Figure 4.5b may have been another reason of the less damage to its frame members. Figure 4.5c shows the lack of transverse reinforcement in the beam-column joints and the insufficient transverse reinforcement and use of plain bars in the columns. It is noted that damage took place in the third story but not the others, due to the formation of a soft and weak story after the failure of the infill walls.

For low- to mid-rise URM infilled RC buildings without vertical stiffness or strength discontinuity, first-story infill walls are expected to be damaged first, since they are subjected to the highest shear forces. However, under bidirectional loading, infill walls of the upper stories may fail under the combination of out-of-plane and in-plane effects (Mosalam 2009b). Infill walls of the third story of the building shown in Figure 4.5c may have failed under such an effect. Collapse of the whole story may have occurred if other columns and beam-column joints were damaged; however, this did not happen, possibly due to the beneficial effect of the short effective duration of the ground shaking as previously explained.

Figure 4.6a shows a similar but more severe situation to that shown in Figure 4.5c, where the third story of a building collapsed. It can be observed that the column sizes are small; therefore, infill walls had a significant contribution to the story stiffness. It can also be observed that some of the fourth-story infill walls failed, while infill walls of the other stories were in place and remained intact. The infill walls in the third and fourth stories likely failed under the combination of out-of-plane and in-plane effects similar to the case mentioned above for the building in Figure 4.5c. After the failure of the infill walls, a soft and weak third story was formed. The presence of stronger beams relative to the columns led to the formation of hinges at both of the column ends, causing the eventual collapse of the story as a result of increasing lateral deformations. Figure 4.6b shows a complete collapse, which is a consequence of the combined effect of all the seismic vulnerabilities mentioned above. Collapse probably, initiated

with damage to the lower stories and continued with the effect of the impact of the upper stories on the damaged lower ones.

The photographs in Figure 4.6 once again show that non-ductile RC buildings with URM infill walls are among the world's most common, yet seismically vulnerable buildings. The locations of these three buildings (the building in Fig. 4.5c with a severely damaged story, the building in Fig. 4.6a with a collapsed story, and the totally collapsed building in Fig. 4.6b) are shown in Figure 4.7. Amongst several possible reasons for the difference in the damage levels of these buildings, one could be the difference in shaking experienced by the buildings which is possible by observing the differences in the peak values of ground motions at the closely located stations AQA, AQG, and AQV (Table 2.1 and Fig. 2.1) and considering the site effects on young sediments (GEER 2009). Another reason could be related to the fact that the collapse state of non-ductile buildings is in a narrow performance band in the sense that a non-ductile building's performance might change from moderate or severe damage to total collapse due to small differences in material strength, construction practice, or workmanship (Sezen et al. 2003).

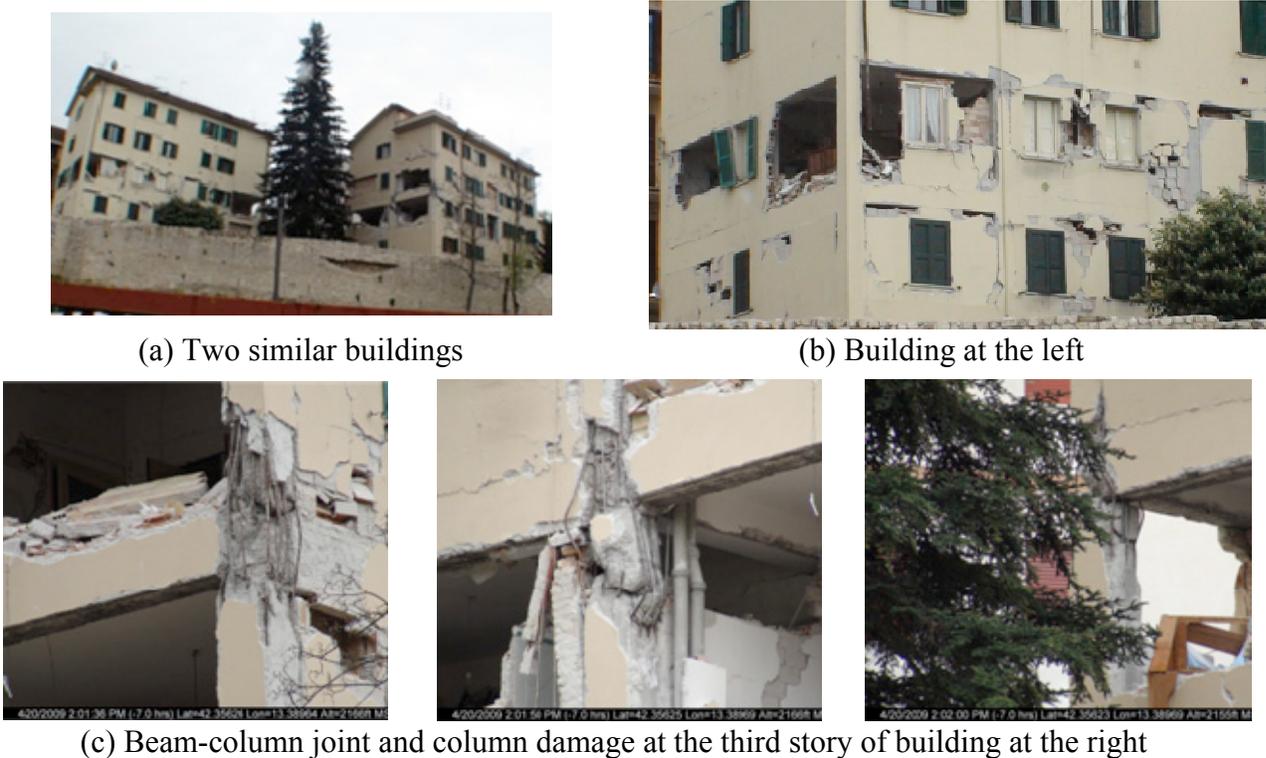


Fig. 4.5 Severe damage in RC frame buildings with URM infill walls



(a) Infill wall failure initiated mid-story collapse



(b) Completely collapsed building with smooth bars and insufficient ties

Fig. 4.6 Partially and completely collapsed buildings

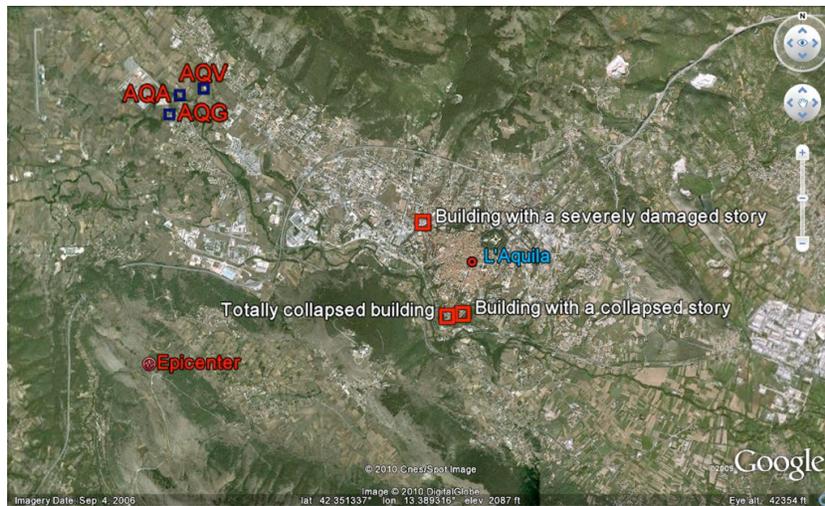


Fig. 4.7 Locations of severely damaged, partially collapsed, and totally collapsed buildings

4.4 FINAL REMARKS

The underlying reasons of damage experienced by RC frames can be summarized as follows:

The formation of soft stories after the failure of stiff and brittle URM infill walls under the interaction of in-plane and out-of-plane forces;

The presence of slender columns leading to two consequences. (1) the weak column-strong beam proportions and (2) the stiffness of the frames being small relative to the infill walls, so that when a story loses its infill walls, it becomes much softer than the other stories; and

Poor seismic detailing in the beam-column joints and confinement regions at the member ends, leading to non-ductile RC frames.

5 Observed Damage in Relation to Other Earthquakes and San Francisco Bay Area

5.1 SIMILAR DAMAGE OBSERVED IN RECENT EARTHQUAKES

Damage observed in the L'Aquila earthquake has similarities with the damage observed in the earthquakes which took place before or after this earthquake in different parts of the world. Therefore, it is informative to draw some comparisons.

Story collapse due to the formation of soft (and weak) stories resulting from the failure of infill walls have been observed in many earthquakes as well as in the L'Aquila earthquake. Two buildings that experienced story collapse in the 1999 Kocaeli, Turkey, earthquake and the recent 2010 Haiti earthquake are shown in Figure 5.1 and Figure 5.2, respectively. The first two stories of the building in Figure 5.1 failed completely, but damage in the upper four stories was limited with even unbroken glass windows. The first story of the building in Figure 5.2 failed, but there was no visible damage in the upper stories. These failures took place as a result of the brittle fracture of first-story infill walls during ground shaking leading to the formation of soft (and weak) stories. Significant stiffness of the infill walls with respect to the RC framing system increased the amount of stiffness change before and after the failure of infill walls. The increased force and displacement demand at the soft stories resulted in the observed gravity load failures. Such first-story infill wall failures were observed in the L'Aquila earthquake (Fig. 4.2) but without leading to story collapse because of the relatively short duration of the earthquake, as explained previously. However, as shown in Figure 4.6, failure of the stiff infill walls of the intermediate stories led to story collapse in the L'Aquila earthquake.



Fig. 5.1 Building with first two stories collapsed — Kocaeli earthquake



Fig. 5.2 Building with first story collapsed — Haiti earthquake (photographs by E. Fierro)

In the 2008 Wenchuan, China, earthquake, there were cases of damaged infill walls protecting the frame members from being damaged (Fig. 5.3), as in the L'Aquila earthquake (Fig. 4.3). However, as shown in Figure 5.3d, damage and failure in URM infill walls is hazardous and should be properly addressed, as stated previously.



(a) Infill wall compression and shear damage



(b) Infill wall shear damage



(c) Infill wall compression damage



(d) Out-of-plane infill wall failure

Fig. 5.3 Damaged infill walls protecting frames in 2008 Wenchuan earthquake (Photographs by B. Li)

Damage shown in photographs from the recent 2010 Chile earthquake resembles that of the L'Aquila earthquake (Fig. 5.4). Figure 5.4a shows minor damage in an infill wall with no damage in the bounding RC frame (see Fig. 4.3 for L'Aquila earthquake). Figure 5.4b shows damage to a historical church built in 1743 (see Fig. 3.3b, L'Aquila). The lost dome of a historical church in Santiago is shown in Figure 5.4c (Fig. 3.3b, L'Aquila). Figure 5.4d presents tie-rods used for arch strengthening (Fig. 3.3e, L'Aquila), and Figure 5.4e shows the out-of plane wall failure at the ninth story of a building (Fig. 4.5a, L'Aquila).



(a) Infill wall damage protecting the frame



(b) Damage at a church built in 1743



(c) Lost dome of a historical church



(d) Tie-rods for arch strengthening



(e) Out-of-plane wall failure at the 9th story of a building

Photographs (a), (b), and (d) by
Degenkolb Engineers

Photographs (c) and (e) from the
New York Times

Fig. 5.4 Photographs from 2010 Chile earthquake with damage like that of L'Aquila earthquake

5.2 LESSONS LEARNED FROM L'AQUILA EARTHQUAKE RELATED TO SAN FRANCISCO BAY AREA

In terms of seismic hazard, L'Aquila earthquake ground shaking can be thought of having similarities to a potential earthquake expected in San Francisco Bay Area, in the sense that the populated city centers are in near-fault locations. However, the L'Aquila earthquake took place on a normal fault, whereas the primary faults in the Bay Area are strike-slip faults for which forward-directivity effects can be expected to be more severe, with the vertical component of excitation being less severe.

Vulnerable structural types in the Bay Area, according to Bonowitz (2009), can be classified as unreinforced masonry, unbraced cripple walls, soft-story wood frame, non-ductile concrete frames, tilt-ups, hillside houses, precast concrete parking structures, pre-Northridge steel frames, and thin-wall steel braced frames. Among these types, unreinforced masonry and non-ductile concrete frames were the most common structural types of the L'Aquila earthquake to experience several levels of damage as discussed above.

Damage experienced by unreinforced masonry structures in L'Aquila earthquake was in the form of out-of-plane failure of walls due to the low quality of masonry, inadequate connection of the walls to the floors and roof, and pounding leading to partial and total collapse for some cases. In the 1989 Loma Prieta, California, earthquake, unreinforced masonry buildings in the Bay Area suffered damage due to out-of-plane brick failure, in-plane brickwork failure, diaphragm flexibility/failure, and pounding. Improper connections between walls and roof or floor diaphragms caused several failures of older URM buildings (Tena-Colunga and Abrams 1992). The earthquake investigation team of the International Masonry Institute observed that unreinforced masonry buildings that had been retrofitted for seismic safety appeared to have performed well (1990). Since then, many URM buildings have been retrofitted, including the Hearst Memorial Mining Building at the University of California, Berkeley, and 19th century structures of Stanford University (Bay Area Seismic Retrofit Map 2010). However, the risk of pounding still exists in many residential buildings around the Bay Area (Fig. 5.5).

As presented in Chapter 4, the L'Aquila earthquake once again showed that non-ductile concrete buildings may lead to substantial damage similar to observations made in many other earthquakes. Similarly, a scenario based on a repeat of the 1906 San Francisco earthquake in the Bay Area today states that a large proportion of deaths and serious injuries would be due to the collapse of non-ductile concrete buildings (Comartin et al. 2008). The Concrete Coalition project, initiated with the purpose of the identification of dangerous non-ductile concrete buildings and the development of solutions to reduce the associated collapse hazard, is currently gathering information on the number and types of pre-1980 concrete buildings that exist in California (Concrete Coalition 2010). Within the scope of the project, a "Top Ten Deficiency Survey" developed by PEER researchers for practicing engineers aims to rank the most frequently encountered failure mechanisms for non-ductile concrete structures based on engineering judgment and experience (Concrete Coalition 2010). The listed ten failure mechanisms are (1) flexurally weak column mechanism, (2) shear-critical columns, (3) captive

columns, (4) splice and joint failures, (5) weak first story, (6) discontinuous walls, (7) severe plan irregularity, (8) deformation compatibility, (9) pounding, and (10) foundation failure. Many of these failure mechanisms were observed in the L'Aquila earthquake, including flexurally weak column mechanism, shear-critical columns, captive columns, joint failures, and pounding. In addition to these ten failure mechanisms, the out-of-plane failure potential of infill walls and the high stiffness of infill walls relative to the bounding frames can be added to this list based on the L'Aquila earthquake damage, since these failures commonly lead to the formation of weak or soft stories during ground excitation.



Fig. 5.5 Buildings vulnerable to pounding effect in San Francisco (Photographs by R. Negrete)

6 Conclusions and Lessons Learned

This report presents a general overview of the seismic hazard and the observed damage for the April, 6, 2009, Abruzzo, Italy, earthquake. Specific observations and lessons learned are summarized as follows:

1. In the near-fault region, horizontal PGA values reached up to 0.63g, with some ground motions having vertical PGA as high as the horizontal. Ground shaking significantly attenuated for far-fault stations. Velocity pulses due to forward-directivity were of moderate intensity.
2. The vertical component pseudo-acceleration spectra of the recorded ground motions match that of the Eurocode. The horizontal component spectra match the Eurocode spectra in the acceleration-sensitive region (i.e., for periods less than 0.5~0.6 sec) but the pseudo-accelerations of the recorded ground motions are much less than the Eurocode values in the velocity sensitive region.
3. Ground motion parameters including PGA, PGV, and spectral acceleration are generally within the median $\pm \sigma$ NGA predictions.
4. The historical URM buildings of the city of L'Aquila and the surrounding towns exhibited damage ranging from wall cracking to severe damage and collapse. The largest damage to historic buildings was observed in small towns located adjacent to L'Aquila, where cases of complete collapse were evident, whereas the historic buildings of L'Aquila, in general, performed better than those located in nearby towns. Damage to the historical buildings is attributed to the cultural preservation philosophy in Italy, which requires rebuilding the historic structures in the same manner and with similar materials as in the original construction. Another reason for the heavily damaged cases was the site amplification in soil deposits.
5. It was observed that cross-ties restraining the out-of-plane deformation of multi-wythe URM walls were effective in limiting the collapse of these types of buildings.

6. Pounding led to partial and total collapse of aggregated historical URM buildings with low material quality.
7. Traditional earthquake design philosophy, which is based on preventing structural and non-structural elements of buildings from any damage in low-intensity earthquakes, limiting the damage in structural and non-structural elements to repairable levels in medium-intensity earthquakes, and preventing the overall or partial collapse of buildings in high-intensity earthquakes, is not suitable for hospitals and other critical structures. As evident from the L'Aquila earthquake, these structures should be designed according to performance-based design principles such that they should remain fully functional following an earthquake.
8. The damage observed in RC frames with URM infill walls varied from small cracking to severe damage and collapse. This damage was attributed to poor seismic detailing such as use of smooth reinforcing bars, short lap splices, insufficient column ties, and insufficient transverse reinforcement in the beam-column joints, leading to non-ductile behavior. Large stiffness of the infill walls relative to the bounding frames and the soft- and weak-story formations after the failure of the infill walls under the combination of in-plane and out-of-plane effects played a major role in the resulting damage and collapse.
9. Out-of-plane failure of infill walls should be accounted for in the design process of RC frames with URM infill walls. Moreover, the in-plane/out-of-plane interaction should be properly considered in the design and retrofit of RC frames.
10. For some of the buildings, a short duration of shaking helped prevent the spread of damage to the frame members after the damage or failure of the infill walls. After the strong part of shaking (i.e., loss of the ground motion intensity), ground motion was not able to damage the RC frame members after these members became vulnerable (due to the formation of soft and weak stories and the non-ductile details of the frames) with the failure of infill walls.
11. Observed failure types of non-ductile RC buildings with and without URM infill walls in the L'Aquila earthquake possess similarities with observations from other recent earthquakes (2008 Wenchuan, China, 2010 Haiti, and 2010 Chile) and with the potential failure types expected in a future earthquake in the San Francisco Bay Area. The out-of-plane failure potential of infill walls and the high stiffness of infill walls relative to the bounding frames should also be considered in the list of non-ductile concrete building deficiencies, as these two anomalies lead to formation of soft and weak stories during ground shaking.

REFERENCES

- Bay Area Seismic Retrofit Map. <http://www.earthquakeretrofit.org> [24 March 2010].
- Bonowitz, D. 2009. Hazardous structural building types identified from Loma Prieta and mitigation policies developed to confront their risk. In *Loma Prieta Earthquake Commemorative Symposium* October 17, San Francisco, CA.
- Boore, D. M., Watson-Lamprey, J., and Abrahamson, N. A. 2006. GMRotD and GMRotI: Orientation-independent measures of ground motion. *Bulletin of the Seismological Society of America* 96(4A): 1502–1511.
- Boore, D. M., and Atkinson, G. M. 2008. Ground-motion prediction equations for the average horizontal component of PGA, PGV, and 5%-damped PSA at spectral periods between 0.01 s and 10.0 s. *Earthquake Spectra* 24(1): 99–138.
- Borri A., De Maria, A. 2009. Eurocode 8 and Italian code: a comparison about safety levels and classification of interventions on masonry existing buildings. In *Eurocode 8 Perspectives from the Italian Standpoint Workshop*, Editor: Edoardo Cosenza, Napoli, Italy.
- Bray, J.D. and Rodriguez-Marek, A. 2004. Characterization of forward-directivity ground motions in the near-fault region. *Soil Dynamics and Earthquake Engineering* 24(11): 815–828.
- Campbell, K. W., and Bozorgnia, Y. 2008. NGA ground motion model for the geometric mean horizontal component of PGA, PGV, PGD, and 5% damped linear elastic response spectra for periods ranging from 0.01 to 10 s. *Earthquake Spectra* 24(1): 139–171.
- Chioccarelli E., and Iervolino I. 2010. Near-source seismic demand and pulse-like records: A discussion for L'Aquila earthquake. *Earthquake Engineering and Structural Dynamics* published online at February 9, 2010.
- Comartin, C.D., Anagnos, T., Faison, H., Greene, M., and Moehle, J.P. 2008. *The Concrete Coalition: building a network to address nonductile concrete buildings*. In *Proceedings of the 14th World Conference on Earthquake Engineering*, October 12-17, Beijing, China.
- Concrete Coalition. <http://www.concretcoalition.org> [24 March 2010].
- Degenkolb Engineers, 2010. *Perspectives*, January Issue, San Francisco, CA, USA. Available from <http://www.degenkolb.com/wp-content/uploads/2010/01/webpadangitalyeq.pdf>.
- Dolce, M. and Manfredi, G. 2009. Research needs in earthquake engineering highlighted by the 2009 L'Aquila earthquake. In *The State of Earthquake Engineering Research in Italy: the ReLUIS-DPC 2005-2008 Project*. Editors: Gaetano Manfredi and Mauro Dolce, Napoli, Italy.
- Earthquake Engineering Research Institute (2009). *Learning from earthquakes: The Mw 6.3 Abruzzo, Italy, earthquake of April 6, 2009*. EERI Special Earthquake Report, June, EERI, Oakland, CA.
- European Commission. Eurocodes: *Building the future -The European Commission website on the Eurocodes*. <http://eurocodes.jrc.ec.europa.eu/home.php> [15 February 2010].
- Geo-engineering Extreme Events Reconnaissance (GEER). 2009. *Preliminary report on the seismological and geotechnical aspects of the April 6 2009 L'Aquila earthquake in Central Italy*. Report No. GEER-016, Editor: J.P. Stewart

- International Masonry Institute. *The Loma Prieta, California, earthquake of October 17, 1989; observations regarding the performance of masonry buildings*. February 1990.
- Istituto Nazionale di Geofisica e Vulcanologia (National Institute of Geophysics and Volcanology) <http://www.ingv.it> [30 January 2010].
- Joyner, W.B., and Boore, D.M. 1981. Peak horizontal acceleration and velocity from strong-motion records including records from the 1979 Imperial Valley California earthquake. *Bull. Seism. Soc. Am.*, 71:2011–2038
- Magenes, G., and Penna, A. 2009. Existing masonry buildings: general code issues and methods of seismic analysis and assessment. In *Eurocode 8 Perspectives from the Italian Standpoint Workshop*, Editor: Edoardo Cosenza, Napoli, Italy.
- Modena C., Casarin F., da Porto F., Garbin E., Mazzon N., Munari M., Panizza M., Valluzzi M.R. 2009. Structural interventions on historical masonry buildings: review of Eurocode 8 provisions in the light of the Italian experience. In *Eurocode 8 Perspectives from the Italian Standpoint Workshop*, Editor: Edoardo Cosenza, Napoli, Italy.
- Mosalam, K.M. 2009a. Lessons for the Bay Area from the Italy earthquake: response of buildings in April, 6, 2009 Abruzzo, Italy earthquake. *EERC Northern California Chapter Newsletter Summer Issue*.
- Mosalam, K.M. 2009b. Seismic evaluation of reinforced concrete frames with masonry infill walls: experiments, observations, and simulations. *11th Canadian Masonry Symposium*, Toronto, keynote paper, May 31-June 3.
- NTC. 2008. *Norme Tecniche per le Costruzioni* D.M. 14 gennaio 2008, Suppl. ord. n.30 alla G.U. n.29 del 4/02/2008
- Oliveira, D.V., Lourenço, P.B. 2004. Repair of stone masonry arch bridges. In *Proceedings of Arch Bridges '04*, Barcelona, Spain, 451-458.
- Pinto, P.E. and Manchini G. 2009. Seismic assessment and retrofit of existing bridges. In *The State of Earthquake Engineering Research in Italy: the ReLUIS-DPC 2005-2008 Project*. Editors: Gaetano Manfredi and Mauro Dolce, Napoli, Italy.
- Power, M., Chiou, B., Abrahamson, N., Bozorgnia, Y., Shantz, T., and Roblee, C. 2008. An overview of the NGA Project. *Earthquake Spectra* 24(1): 3–21.
- Sezen, H., Whittaker, A.S., Elwood, K.J., and Mosalam, K.M. 2003. Performance of reinforced concrete buildings during the August 17, 1999 Kocaeli, Turkey earthquake, and seismic design and construction practice in Turkey. *Engineering Structures* 25(1): 103-114.
- Somerville, P. G., Smith, N. F., Graves, R. W., and Abrahamson, N. A. 1997. Modification of empirical strong ground motion attenuation relations to include the amplitude and duration effects of rupture directivity. *Seismological Research Letters* 68(1): 199–222.
- Tena-Colunga, A., and Abrams, D. P., 1992. *Response of an unreinforced masonry building during the Loma Prieta earthquake*. Structural Research Series, No. 576, Department of Civil Engineering, University of Illinois at Urbana-Champaign.
- Trifunac, M.D. and Brady, A.G. 1975. A study of the duration of strong earthquake ground motion. *Bulletin of the Seismological Society of America* 65: 581-626.
- United States Geological Survey (USGS). <http://www.usgs.gov> [10 January 2010].

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