Recorded Motions of the 6 April 2009 M$_w$ 6.3 L'Aquila, Italy, Earthquake and Implications for Building Structural Damage: Overview

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The normal-faulting earthquake of 6 April 2009 in the Abruzzo Region of central Italy caused heavy losses of life and substantial damage to centuries-old buildings of significant cultural importance and to modern reinforced-concrete-framed buildings with hollow masonry infill walls. Although structural deficiencies were significant and widespread, the study of the characteristics of strong motion data from the heavily affected area indicated that the short duration of strong shaking may have spared many more damaged buildings from collapsing. It is recognized that, with this caveat of short-duration shaking, the infill walls may have played a very important role in preventing further deterioration or collapse of many buildings. It is concluded that better new or retrofit construction practices that include reinforced-concrete shear walls may prove helpful in reducing risks in such seismic areas of Italy, other Mediterranean countries, and even in United States, where there are large inventories of deficient structures. [DOI: 10.1193/1.3450317]

INTRODUCTION

THE EARTHQUAKE: GENERAL INFORMATION

A significant normal-faulting earthquake shook the Abruzzo Region of Central Italy on 6 April 2009 starting at 1:32:39 UTC (Figure 1). The magnitude of the earthquake, according to Italian Istituto Nazionale di Geofisica e Vulcanologia (INGV), is M$_w$=6.3 (M$_s$=6.3, M$_l$=5.8). The coordinates of the epicenter are 42.348 N, 13.380 E and the hypo-

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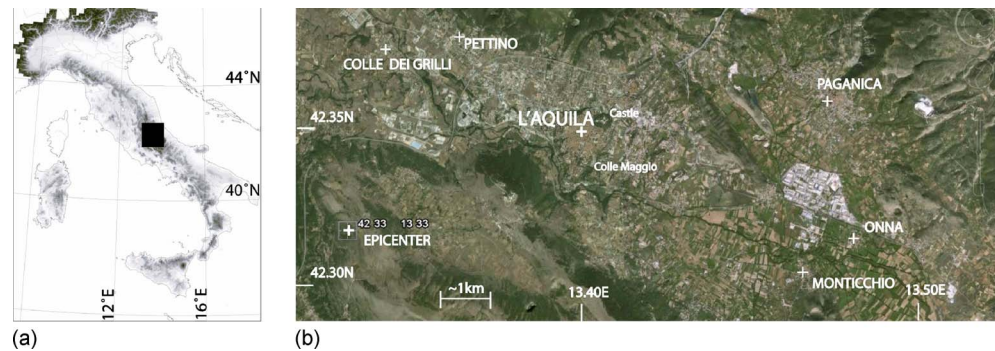[b] AIR Worldwide, San Francisco, CA USA
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Figure 1. (a) General map of Italy depicting the earthquake region. (b) Map of the earthquake region near L'Aquila (the base map is obtained from Google Earth).

central depth was 9.5 km. Aftershocks of the earthquake define a remarkably simple and planar rupture surface that dips 55° to the southwest and passes directly beneath the town of L'Aquila at a depth of approximately 6 km (Chiarabba et al. 2009). The earthquake was most likely caused by rupture of the (normal) Paganica Fault. Geologists traced an approximately 2.5–3 km long surface rupture near Paganica and Bazzano (EMERGEO Working Group, in press; http://www.earth-prints.org/bitstream/2122/5036/1/report_emergeo.pdf). Preliminary modeling of the coseismic surface displacements by the Earthquake Remote Sensing Group at INGV using InSAR indicate that the rupture principally propagated 15 km updip and 20 km along strike to the southeast from the hypocenter (Atzori et al. 2009).

As of early May 2009, 305 people lost their lives and over 1,500 people experienced injuries in the earthquake. A significant amount of losses in terms of lives (approximately 134 people) occurred in a few reinforced-concrete buildings (about 1% of the whole reinforced-concrete construction stock). The largest town in the area, L'Aquila, with a population of 66,813, was devastated by the earthquake. Central L'Aquila is rated as 8.5 on the MCS intensity scale (Galli and Camassi 2009). The main event left a total of 64,812 people displaced from their homes, with approximately 32,100 people living in tents and 32,700 lodged in hotels along the Adriatic coast (as of 8 May 2009, Italian Department of Civil Protection, DPC, http://www.protezionecivile.it). For example, in L'Aquila, as well as in other smaller towns and villages, no one was allowed to stay in their homes for fear of further collapses of the already-damaged buildings. It is important to add that in the small village of Onna, which had a total population of 700, 40 people lost their lives; there, the rupture was just 3 km below the surface and the reported macroseismic intensity (MCS) was 9.5 (Galli and Camassi 2009). Unofficially, approximately 60,000 structures were damaged. It is estimated that approximately 10% (6,000) of these are engineered structures. As of 8 June 2009, about 53,000 buildings located outside of the most damaged areas that were subjected to mandatory evacuation had been inspected by 2,000 technical teams of specially trained engineers. About 54% of the buildings were judged ready for re-occupancy and 29% unsafe for occupancy (DPC 2009). Figure 1 shows

the general location of the earthquake region and the epicenter in relation to settlements and other points of interest, respectively, which are referred to in this paper.

Fifty-eight accelerometer stations belonging to the Italian Strong Motion Network (RAN, Rete Accelerometrica Nazionale, managed by DPC) were triggered by the main shock. In addition, the broadband seismometers of the INGV network (http://portale.ingv.it/; Amato et al. 2006) provided 113 on-scale recordings, within epicentral distances of more than 700 km, from which strong motion parameters such as peak ground accelerations (PGA), peak ground velocities (PGV), and response spectral values are extracted. Finally, the INGV station, AQU[1] (Mazza et al. 2008), the closest one to L'Aquila center was also equipped with an accelerometer that captured the main shock. Because they may have affected the behavior and performance of structures, it should be noted that, through the end of June 2009, there have been 22 $M > 4$ aftershocks, each recorded by an average of approximately 40 strong-motion stations. The largest of these events are an $M_w = 5.6$ on 7 April 2009 located to the south of the main shock and two events with magnitudes of $M_w = 5.4$ and 5.3 that occurred on 9 April 2009 north of L'Aquila. Hence, there is a wealth of data from this earthquake. Unfortunately, there are no records from L'Aquila's historical center.

Strong earthquakes are not completely unusual for the Abruzzo Region. Within the past 700 years, at least five damaging earthquakes occurred in the region, including the two largest events in the area with very similar macroseismic characteristics in 1461 and 1703 (Rovida et al. 2009). The largest recent earthquake ($M_w = 7.0$) in the region prior to 2009 occurred in 1915 beneath the Fucino Basin and caused extensive damage in L'Aquila about 35 km from the epicenter near Avezzano (Ward and Valensise 1989, Amoruso et al. 1998, Valensise 2009).

The largest town in the region, L'Aquila, lies approximately 110 km east of Rome. L'Aquila and its satellite settlements nearby (e.g., Pettino, Onna, Monticchio, Bazzano, and Paganica) shook at various levels of acceleration (but certainly > 0.3 g). With a few exceptions, such as Monticchio which lies within the immediate epicentral area and very close to Onna (~ 1.5 km away), many other towns and villages, including L'Aquila, Pettino, and Onna, were heavily damaged and completely evacuated, with security-controlled entrance imposed and no economic or social activity in the months following the event.

OBJECTIVE AND SCOPE

The purpose of this paper is to review the general characteristics of the building stock in the region and to preliminarily correlate the observed structural damage to recorded main-shock strong ground motion data. Aftershocks are not considered. In addition, data collected from temporary arrays (Azzara et al. 2009) and new strong motion stations are not studied in this paper. At this time, no detailed analysis of any one particular building is attempted. Damage to structures (e.g., bridges and viaducts) is excluded in the discussion.

[1] AQU is part of MedNet Network that belongs to INGV
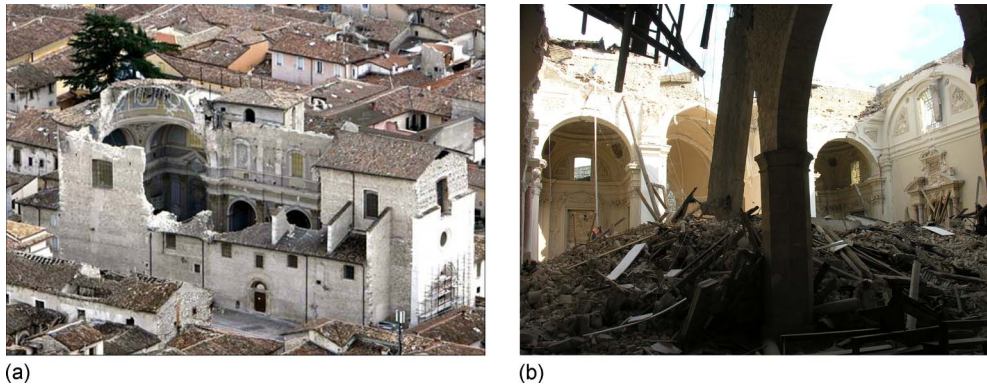
Figure 2. Most historical masonry buildings did not fare well during the shaking: (a) Santa Maria in Paganica, (b) Transept of Santa Maria in Collemaggio, L'Aquila.

TYPES OF STRUCTURES AND DAMAGE

Reinforced concrete (RC) shear walls are not commonly used in construction in this earthquake region. Very few steel structures exist. Hence, the dominant types of construction in the region can be classified as:

- Older buildings or historical buildings, considered as "cultural heritage," are mainly constructed of stone or brick masonry. A significant percentage of such structures (including historical churches), especially those with poorly maintained walls and without strengthening devices (e.g., tie rods), were damaged (Figure 2). In general, historical masonry construction is of poor quality (e.g., lack of connections, poor mortar, etc.). Steel or wood ties have improved the behavior avoiding in various cases local and global collapses and the overturning of facades.

- Typical Mediterranean type of construction of low-rise (two to four stories) to mid-rise (five to eight stories) buildings of reinforced concreted (RC)-framed structural system with hollow clay masonry infill walls and with various architectural and structural vertical and in-plan layout designs (Figures 3, 5, and 6). Due to a desire to provide weather insulation, there are commonly unreinforced infill walls, almost all built with hollow bricks at least two and sometimes three layers thick. This type of reinforced concrete buildings were constructed in large numbers following World War II and most after 1960.

- Industrial buildings (precast panels, similar to tilt-up buildings in the United States, and a few of steel construction).

In general, recently constructed RC-framed structural systems with infill walls performed better. In many cases, the more recent RC-framed buildings with infill walls were also damaged, but the damage was usually limited to nonstructural components while the framing system remained intact. Not surprisingly, older and nonductile or less ductile buildings suffered the heaviest damage. Very few soft-story or pancake-type col-

(a)   (b)
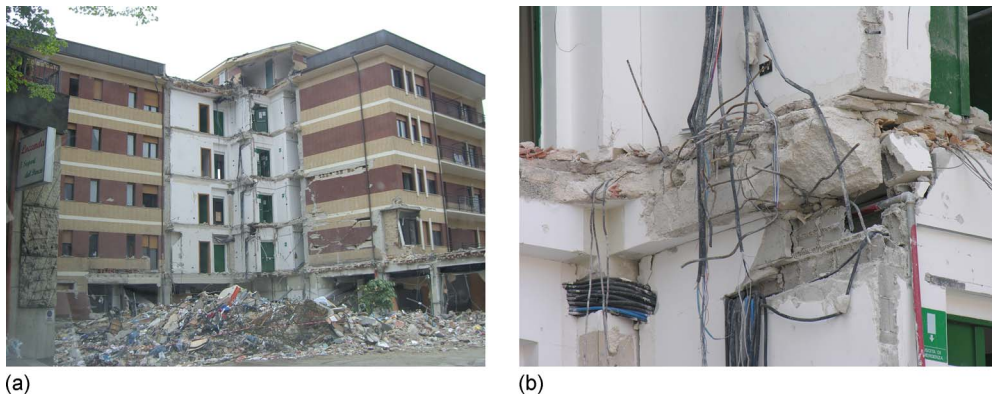
Figure 3. (a) Post-earthquake view of the site where a reinforced concrete framed building with infill walls collapsed during the earthquake. The visible rubble is due to the demolition of the heavily damaged part of the building. (b) Poor detailing of joints and apparently poor concrete quality may have contributed to its fate. The pictures are of a college student dormitory building that partially collapsed and killed about eight students.

lapses were observed. Figures 3–9 show some of the typical types of structures and damage patterns. However, the variation of the vulnerability characteristics of reinforced buildings is significant. As observed in many cases, many collapsed buildings are very close to buildings that survived the earthquake with minor damage. Due to the variability of the buildings' vulnerability and the variability of the ground motion and site effects, the observed damage distribution is significantly irregular.

TYPES OF DAMAGE

In this earthquake, as well as in other earthquakes, structural damage can be generalized to be caused by three main reasons:

- Structural deficiency: Caused by design or construction process and/or age, lack of ductility, deficient materials (e.g., use of smooth instead of deformed reinforcing bars, even though smooth bars were permitted by law at the time of construction of many of the existing building inventory) and/or workmanship, deficient shear and/or longitudinal reinforcement, deficient detailing of joints (e.g., Figure 3). Most damaged RC-framed buildings with infill walls had poor detailing and insufficient shear reinforcement (stirrups and cross-ties) with larger than requisite spacing and insufficient diameter and/or vertical reinforcement. Concrete quality was questionable in most buildings that collapsed or suffered heavy damage. Most of the damaged buildings would not meet what is known as Hassan index (Hassan and Sozen 1994) that stipulates that there must be a minimum percentage area of lateral force-resisting elements (columns and walls) on the ground floor compared to the total floor area of a building in order to improve its performance.

Figure 4. (a) Condition of Hotel Duca Degli Abruzzi in L'Aquila before the earthquake as obtained from Google Maps Street View and (b) the post-earthquake condition observed from the ground. It is possible to observe the presence of a significant irregularity in elevation between the ground and the first floor. (c) Before and (d) after earthquake condition of another collapsed building (irregularity in elevation at intermediate floor) in L'Aquila assessed by similar methods.

- Structural layout: Architectural defects such as large eccentricity or layout with respect to nearby structures. These effects can cause significant shaking variation that may include significant torsion, pounding, short columns, soft stories) (Figures 4–6).
- Actual ground shaking that exceeds design levels: In other words, larger demand than capacity of structures. The larger shaking can sometimes be caused by site effects including basin and topographical effects. Also, possible pulse effects due to directivity can add additional demand to structures for which enough capacity could not have been designed for (e.g., Figures 7–9).

Specific studies of the damages to different types of construction are also reported by Verdearame et al. (2009) and Calderoni et al. (2009).

(a)   (b)
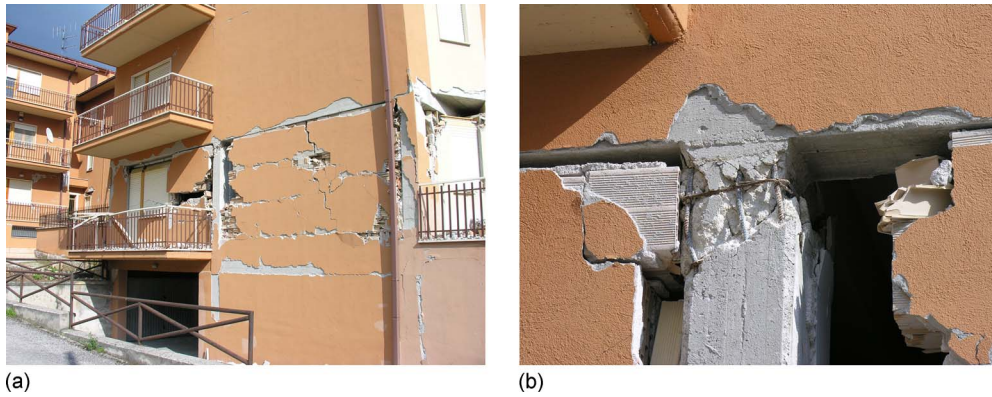
Figure 5. Although damaged and with poor shear rebar detailing, the infill walls (b) may have prevented more severe damage and/or collapse of this building (a).

MAIN-SHOCK RECORDING STATIONS AND RECORDS

GENERAL INFORMATION ON RECORDING STATIONS

Fifty-eight of the approximately 300 digital strong-motion stations operated by the Italian Strong Motion Network (RAN), managed by the Department of Civil Protection (DPC) of Italy, recorded the main shock (http://www.protezionecivile.it/). In addition, 113 broadband seismometers of the INGV network also recorded the earthquake (http://portale.ingv.it/monitoring/). Two of these stations, AQK (RAN) and AQU (INGV), equipped with an STS2 seismometer and an accelerometer, are located at the perimeter of the town of L'Aquila. Within one week of the main shock, a table containing coordi-


(a)   (b)

Figure 6. Perhaps unintentional vertical layout error (with the new building close to the older one with unmatching floor and roof elevations) caused pounding damage to the new building on the right.

(a)   (b)

Figure 7. A majority of buildings in Onna (MCS 9.5 according to Galli and Camassi 2009). Mostly older, poor, nonductile masonry and un-engineered suffered heavy damage or collapsed.

nates, peak accelerations, and epicentral distances of 56 stations was released by RAN and drew attention to large peak accelerations recorded at distances close to the epicenter (Table 1). Within ten days, uncorrected acceleration time-series for all main-shock records and several aftershocks were released by RAN. A detailed study of the parameters of the strong-motion data is presented by Ameri et al. (2009). Six strong-motion stations at epicentral distances <6 km, four of the Aterno Valley array stations (AQA, AQG, AQV, and AQM) and two closer to downtown L'Aquila (AQK and AQU), are located on the hanging wall of the ruptured fault (i.e., zero "Joyner-Boore" distance, R_{JB}; Boore et al. 1997) and recorded >0.3 g peak ground accelerations, with the largest peak of >1 g

(a)   (b)
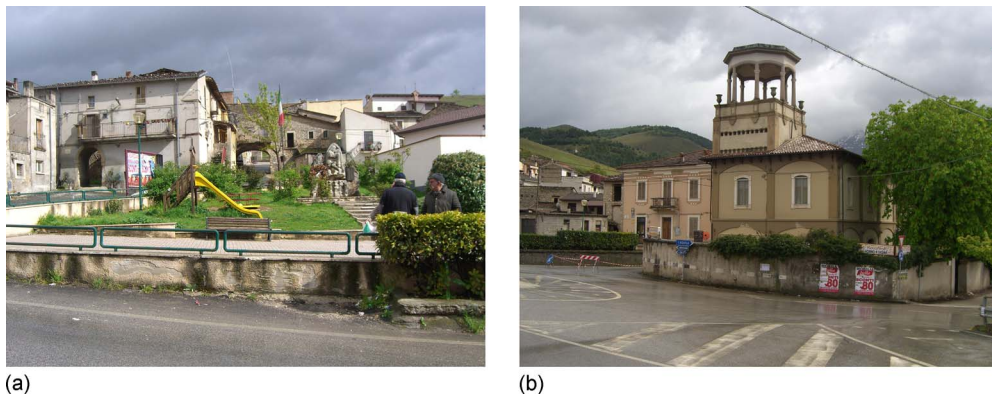
Figure 8. Although very close to Onna, the village of Monticchio suffered minimal damage (MCS 6.0 according to Galli and Camassi 2009). This is attributed to Monticchio being on firmer (Pleistocene) mainly silty and clayey lacustrine deposits, while Onna is on Holocene alluvial deposits (APAT 2006).

Figure 9. Cases where topographical effects may have played a role influencing the shaking imposed on these buildings. (a) A building with damages to the infill walls. (b) The bus depot behind which there is a retaining wall above which station AQK is housed. Arrow shows GPS antenna of the station. (c) Via Gualtieri d'Ocra, L'Aquila: mid-story pancake collapse, (d) another partial collapse of a building founded on a slope.

(clipped) at station AQM and a PGA of 0.67 g at station AQV (Table 1). RAN station, GSA, at an epicentral distance of 14.1 km and on the footwall of the fault, recorded only 0.15 g.

GENERAL INFORMATION ON GEOLOGY AS RELATED TO STATIONS

General views of the topography and geology of some of these important stations recording the earthquake are shown in Figures 10 and 11. An updated version of the geology map can be found in DiCapua et al. (2009). Relative locations of stations AQK and AQU are provided in Figure 10 also. A calcareous geological formation characterizes L'Aquila and its neighborhoods from south to east as detailed in several references (De Luca et al. 2005, APAT 2006, DiCapua et al. 2009, GEER 2009); in Italy, this calcareous rock is known as the "Scaglia formation." In a more descriptive detail, L'Aquila is set on an alluvial terrace that forms the left bank of Aterno River. The alluvial depos-

Table 1. Partial RAN-released list identifying the closest stations that recorded >0.1 g on hanging wall and footwall of the fault, and station AQU (INGV broad band station that also co-houses an accelerometer; compiled from several Italian sources including: http://itaca.mi.ingv.it/ItacaNet/, EC8 site classification from GEER 2009, also in Appendix A).

Station Name/Record Name/Lat & Long.	Station code	R_{JB} distance (Km)	Epic. distance (Km)	EC8 site class	PGA (cm/s2)	PGV (cm/s)	Arias Intensity (cm/s)	Housner Intensity (cm)
Stations with PGA > 0.1 g on hanging wall of the fault								
V. Aterno Moro/ [42.379N, 13.349E]	AQM	0	5.2	A	1000 (**saturated**)	42.18	435.4	90.1
V. Aterno—Centro Valle/GX066 [42.377N, 13.344E]	AQV	0	4.9	B	646.1	42.83	285.7	94.5
V. Aterno—Colle Grilli/FA030 [42.373N, 13.337E]	AQG	0	4.4	A	506.9	35.54	137.0	92.2
V. Aterno—fiume Aterno/CU104 [42.376N, 13.339E]	AQA	0	4.6	B	435.6	32.03	175.0	86.1
L'Aquila parcheggio/AM043 [42.345N, 13.401E]	AQK	0	5.6	B	347.2	36.21	128.9	68.1
L'Aquila Castello (INGV) [42.354N, 13.402E]	AQU	0	5.8	B	309.5	35.00	71.0	78.0
Stations with PGA > 0.1 g on foot wall of the fault								
Gran Sasso/EF021 [42.421N, 13.519E]	GSA	0	14.1	A	149.1	9.84	44.0	17.8

its that constitute the terrace are lower Quaternary in age and are constituted of ce-mented breccias with limestone boulders and clasts in a marly matrix. The breccias have a thickness of some tens of meters, and overlay lacustrine sediments formed mainly of silty and sandy layers and minor gravel beds (De Luca et al. 2005, GEER 2009, Di-Capua et al. 2009, APAT 2006). Limestone units outcrop to the northeast and southwest (Figure 11). Stations AQG and AQM are on limestone, AQK and AQU are on breccias, and the other stations are on an alluvium layer sitting on limestone. Further details of the geology of the area can be found in De Luca et al. (2005), APAT (2006), DiCapua et al. (2009), and GEER (2009). Although geological studies are not within the scope of this paper, it should be noted that similar calcareous geological base found in other regions has been associated with severe damage to structures during earthquakes; for example, during the 1999 Izmit, Turkey, earthquake, numerous collapses of buildings—and con-sequently, large numbers of lives lost at Avcilar, east of central Istanbul and about 100 km from the epicenter of that earthquake—were attributed to the amplification caused by such calcareous formations under Avcilar (USGS 2000).

(a)   (b)
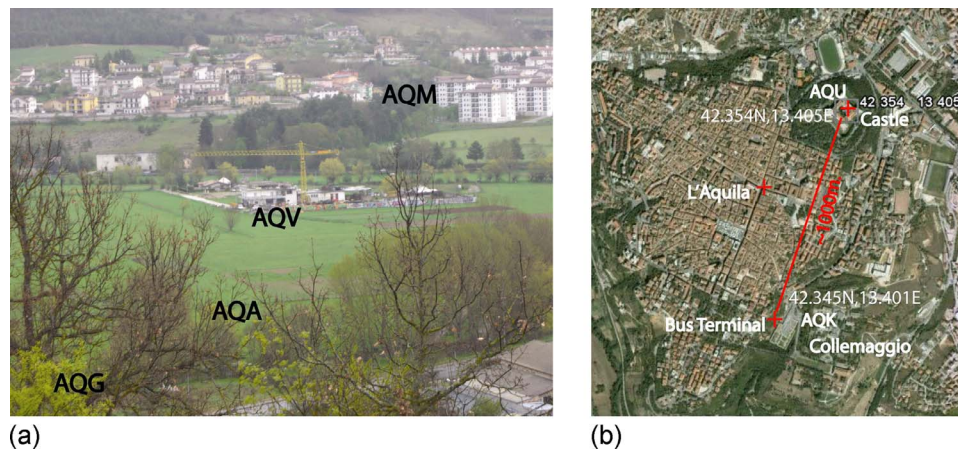
Figure 10. (a) Strong-motion stations AQG (hill), AQA (valley edge), AQV (valley center), and AQM (slope) as seen from near the location of AQG at Colle dei Grilli (rock site). AQM, close to heavily damaged area of Pettino reportedly recorded >1 g. (b) Relative locations of strong-motion station AQK and broadband station, AQU, both at the perimeter of the town of L'Aquila. AQU is within grounds of the damaged L'Aquila castle.
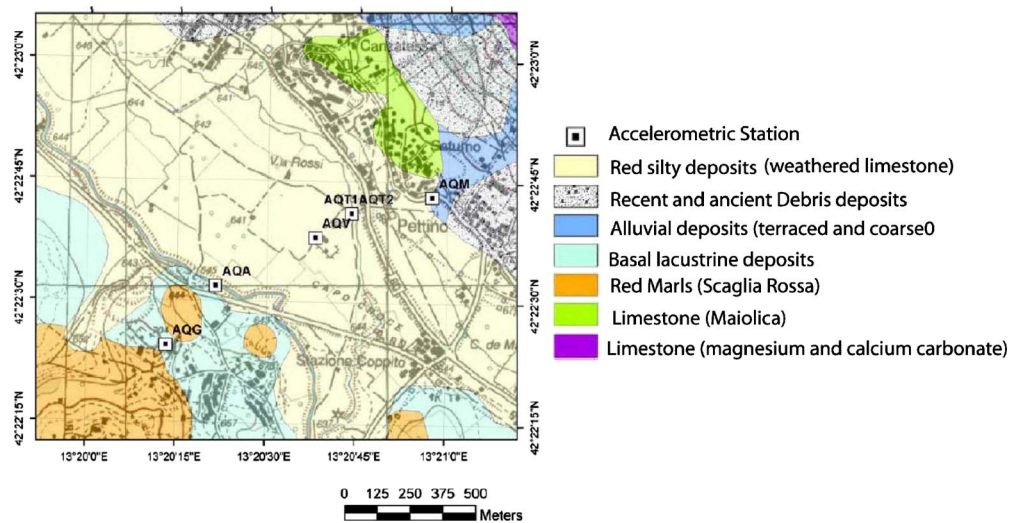
Figure 11. General geology of the area where strong-motion stations that recorded the largest peak accelerations are deployed (Figure adapted from RAN web site of DPC: http://www.protezionecivile.it/, also in Ameri et al. 2009). Station AQM recorded >1 g. Stations AQT1 and AQT2 have been removed before the earthquake.

Data recorded at stations AQM (>1 g), AQK, and AQU are of particular interest as they are close to heavily damaged areas (e.g., AQM close to Pettino and AQK and AQU in the immediate perimeter of L'Aquila). A panoramic view of part of the Aterno Valley Array stations from Colle dei Grilli to Pettino is seen in Figure 10. A brief description of the site conditions follows (EC8 [2004] classes are reported in Table A1):

- Station AQG may have topographical and lithological amplification effects, as it sits on a slope of weathered calcareous rock.

- Station AQV has a velocity profile from cross-hole measurement showing a shear-wave velocity (V_s) inversion between 15 m and 30 m and a V_{S30} of about 475 m/s (http://itaca.mi.ingv.it/ItacaNet/). At this station, there is a panel fence wall within $0.15–0.2$ m of the instrument pad. The embedment depth of the panels, and their effect on the instrument pad motions are not known. Furthermore, there is a construction crane within $6–7$ m of the pad, and its effect is not known.

- Station AQA is similar to AQV with a lesser thickness of Holocene alluvium deposits.

- Station AQM (record clipped at 1 g) is located at the northeast corner of the Aterno Valley Array and on a terrace between two retaining walls. On the basis of the available geological information, the site is rock/stiff site (EC8 class A), consistent with H/V ratios showing peaks around 10 Hz (Ameri et al. 2009). Buildings close to this station were observed to have suffered only minor damage or no damage. Hence, this record is further discussed below.

- Station AQK behind the L'Aquila Bus Station building is on top of a retaining wall. The Bus Station building suffered considerable nonstructural and contents damage. Next to the retaining wall is a tunnel that connects the bus station to downtown. All of the available H/V ratios show a remarkable amplification at 0.6 Hz as also demonstrated by De Luca et al. (2005) using weak motion and ambient noise data. According to these authors, downtown L'Aquila is set on a fluvial terrace with alluvial deposits composed of breccias with limestone boulders and clast in a marly matrix. These deposits called "megabrecce" lie on lacustrine sediments that reach their maximum thickness, around 250 m, in the center of L'Aquila.

- AQU is located in an underground vault beneath the north tower of the L'Aquila Castle at the northeastern corner of the old city of L'Aquila and is laying on the same kind of soil described for AQK.

More detailed descriptions of the sites and relevant classifications can be found in Di Capua et al. (2009) and http://esse4.mi.ingv.it/images/stories/Classificazione_Sito_Stazioni_RAN_AQ.pdf).

IMPORTANT RECORDED GROUND MOTIONS AND SPECTRA

Figure 12 shows acceleration plots of the five stations (AQA, AQG, AQK, AQV, and GSA). Their 5%-damped elastic response spectra (for horizontal components) are plotted in Figure 13. Also shown in this figure is the 2008 Italian code design spectrum for rock site with a return period of 475 years (10% probability of exceedence in 50 years; NTC 2008). It is apparent that the response spectra of the records exceeded the most recent
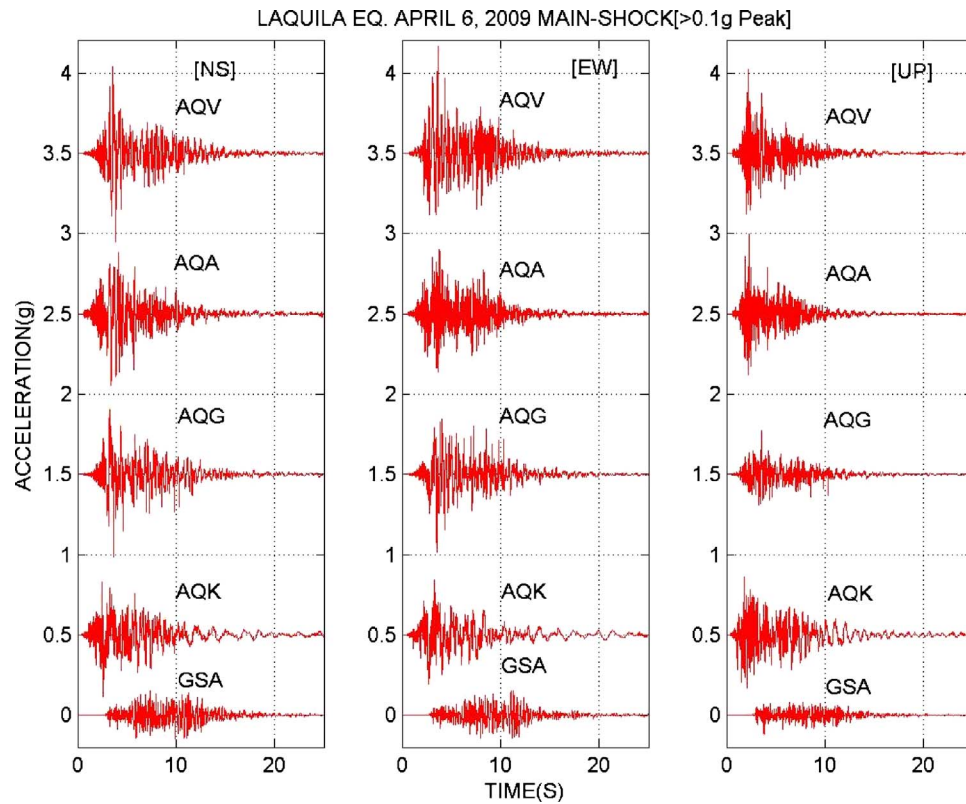
Figure 12. Time-history plots of five stations that recorded >0.1 g. The records are not time synchronized.

up-to-date code design response spectrum. More research should be devoted to this aspect, because some stations could have also experienced significant site amplification effects. Hence, none of the damaged structures in L'Aquila were likely designed (or constructed) with capacity compatible with the demands of the 2008 code design spectrum in Figure 13.

While comparison of elastic response spectra to the 2008 Code is instructive, the comparison of the response spectra for the three largest PGA recordings (excluding AQM) with the 1996[2] code and 2008 code with different soil classes is even more illu-

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[2] Simplified seismic design codes emerged following the 1908 Messina earthquake. L'Aquila was classified as being in second seismic zone of the two-zone 1915 code. Following 1972 Ancona earthquake, in 1975, first serious code emerged, and in 1985, following the 1980 Irpinia earthquake, this code was further improved with three zones. In 1996, two ministerial level declarations (DM 1996a and 1996b) further improved the 1975 code by allowing the use of the limit state method. In 2003, the code was updated with four zones. In 2007, hazard maps were developed and incorporated into the 2008 NTC 2008 code. It is likely that most of the engineered buildings in L'Aquila (certainly the buildings at Pettino) were designed according to the code used between 1975 and 2003.
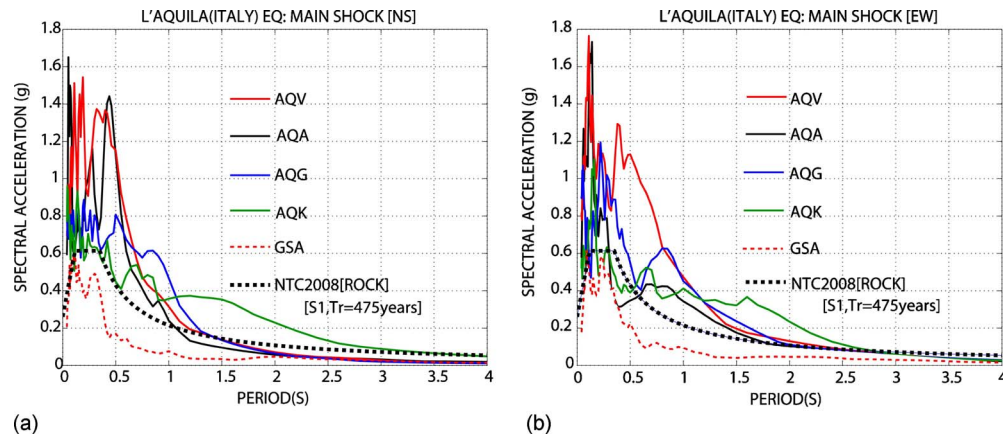
Figure 13. Response spectra for 5% damping for the five stations that recorded >0.1 g and comparison with the 2008 Italian Code Spectrum (for 475 years return period and rock site).

minating (Figure 14). Most modern buildings in the area likely used the 1996 code and not the recent 2008 code. In constructing the 1996 design response spectrum, we assume a structure factor about 4 for regular frames (but very variable in type and material) and
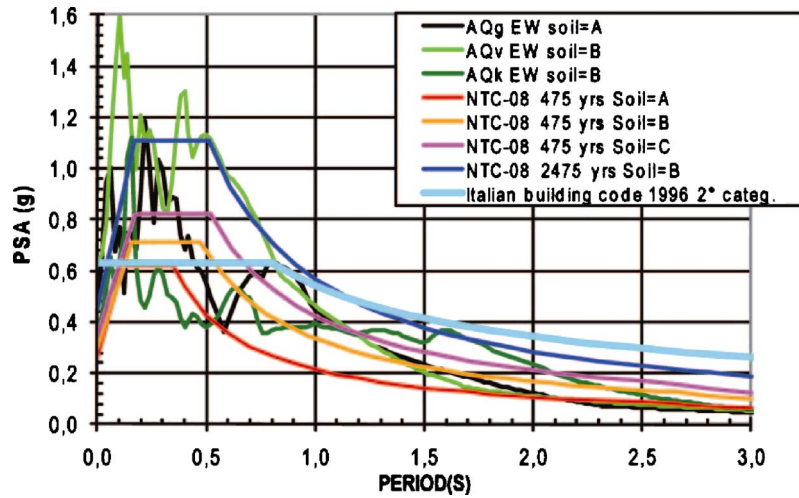
Figure 14. Response spectra for 5% damping for the three highest PGA recording stations (excluding AQM) and comparison with the 1996 and 2008 Italian Code Spectrum (for 475 years return period and different soil classes). Assumptions in construction of the 1996 Code Spectrum are: structure factor 4 for regular frames variable in type and material and a reduction factor of resistance of 1.5 (variable between the materials). For reinforced concrete, 1.5 is adopted, but it may vary between 1.35 and 1.5, which is an intermediate value between that of concrete and steel.
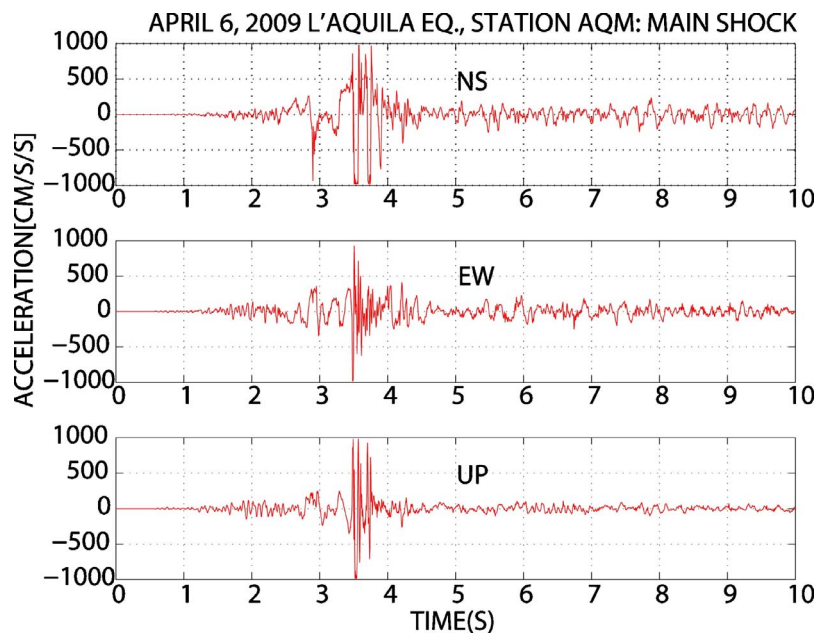
Figure 15. Acceleration time-history of the AQM record shows clipping at 1 g. High frequency pulses dominate the record 3.5 s after arrival. The clipping is attributed to loose anchorage of recorder to the mat of the station (Nicoletti 2009). Data is not used in further deliberations of this paper.

a reduction factor of resistance of 1.5 which is very variable between materials. For reinforced concrete, the reduction factor is accepted to be between 1.35 and 1.50 considered to be an intermediate value between that of concrete and steel.

Because it drew great attention immediately after the earthquake, the large peak acceleration recorded at AQM (Figure 15), by the consensus of these authors at the time of writing of this paper, was deemed to be of very limited engineering significance.[3] This is because the AQM record shows clipping (acceleration greater than 1 g) both on vertical and horizontal components due to a short-duration high-frequency (>10 Hz) pulse 3.5 seconds after the first arrival that is not seen at nearby sites. The saturation does not allow the use of the entire waveform for evaluating velocity or displacement. Hence, the correlation between this record and damage cannot be established in a satisfactory manner. We also note the lack of extensive damage to the buildings (most of them six stories) in the immediate vicinity of this station.

Except for a two-story building in the immediate vicinity of station AQV, the immediate vicinity of the valley close to AQA and AQV are not built up, and therefore the

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[3] Subsequent to the initial submittal of this manuscript, staff from DPC have verified that there was partial loss of anchorage of the recorder to the station mat (Nicoletti 2009).
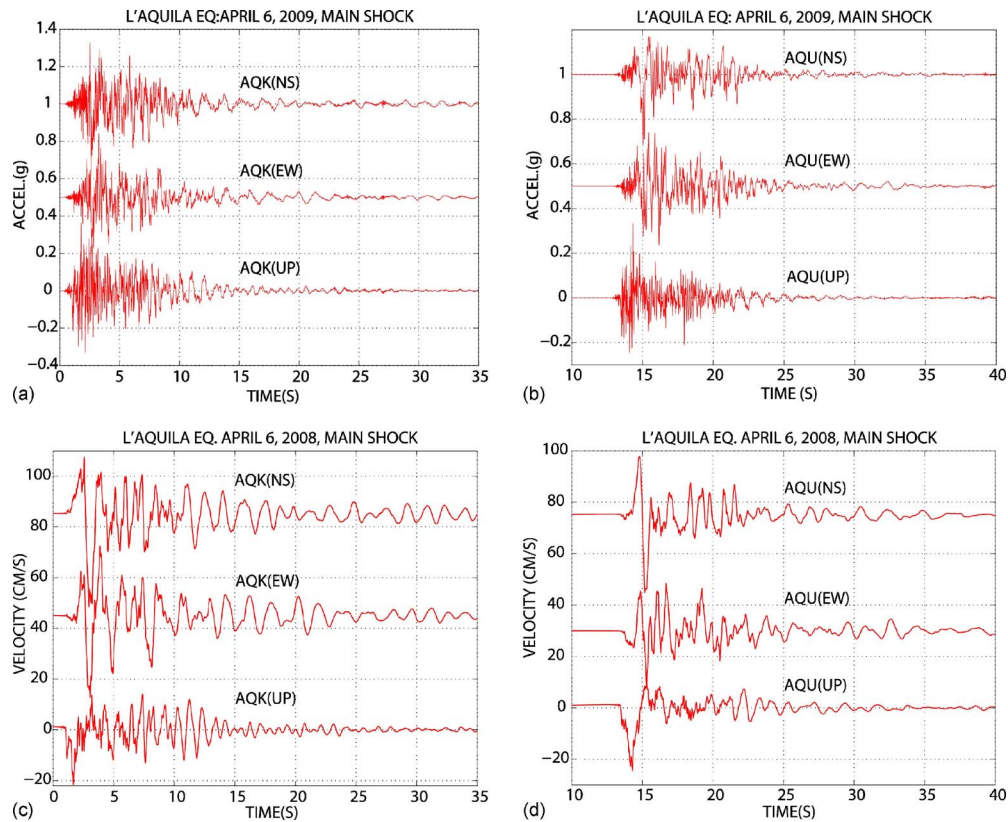
Figure 16. (a) Recorded accelerations and (b) velocities at stationd AQK and AQU. There is no time synchronization between the records at AQK and AQU.

motions recorded at these two stations may not be representative of the motions in L'Aquila. The stations AQG and GSA are not close to L'Aquila either. Therefore, in the absence of data from the historical center of L'Aquila, the ground motions that the structures within the town of L'Aquila most likely experienced are best represented by those recorded at stations AQK and AQU, both within the perimeter of the town and only ∼1 km apart (Figure 10). To further emphasize this point, it is noted that the two most important landmarks of the town of L'Aquila—the L'Aquila Castle (the grounds of which house the station AQU) and Collemaggio, the historical church of L'Aquila near AQK—were also both heavily damaged along with the majority of the buildings in L'Aquila. Thus, for comparison, in Figure 16, we present detailed time-history plots of the accelerations and velocities at AQK (separately from Figure 13) and AQU. Intense double sided velocity pulses are quite distinct on both the AQK and AQU records. Such velocity pulses occurring in the beginning of strong shaking are typical of near-fault motions, and they impart significant input energy to structural systems. In Figure 17, the response spectra of accelerations recorded at these two stations are superimposed for NS and EW directions, respectively, and compared to
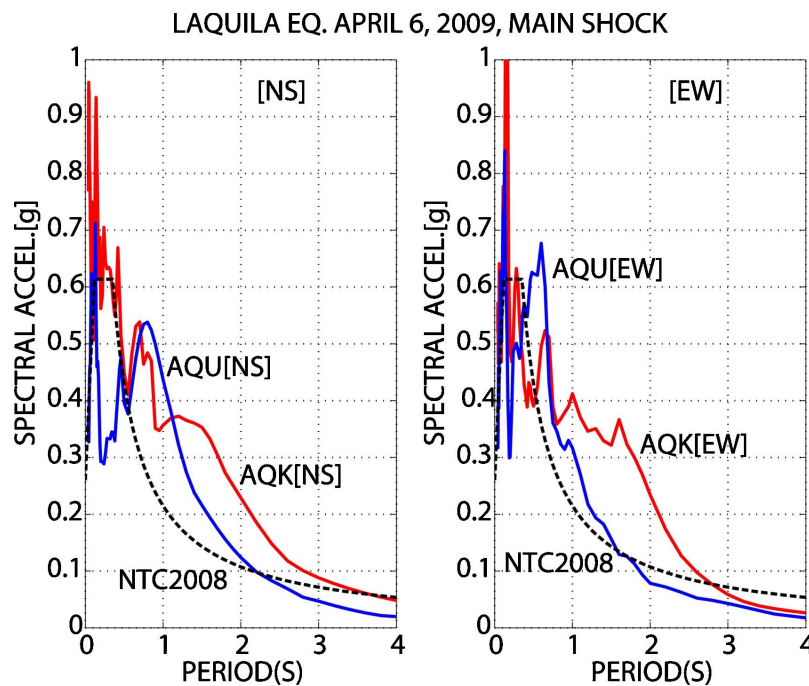
Figure 17. Comparative 5%-damped elastic acceleration response spectra of NS and EW components of accelerations and that of the 2008 code only.

the latest code spectrum. The amplitude spectra of accelerations recorded at these two locations in the perimeter of L'Aquila are compared to that from AQV (in the valley) in Figure 18. It should be noted here that there are many other studies on the spectra of this earthquake. In their studies, Chioccarelli et al. (2009) present a variety of spectra but do not include any conclusions. Petti and Marino (2009) compare elastic spectra at close source with the elastic spectral demands of the latest Italian Code (NTC 2008) and conclude that in the short period range, the demand is considerably severe when compared with the latest code spectra.

Both the response spectra and amplitude spectra indicate similarities in frequency content of the motions recorded at AQK and AQU and definitely expose the fact that the shaking (in the free-field) is rich in frequencies in the ranges 1−4 Hz (0.25−1 s) and 5−8 Hz (0.12−0.2 s), which are similar to the fundamental frequencies of vibration of one-to-eight-story buildings in L'Aquila and in other parts of the region. This would be particularly true for less-stiff, strength-deficient, low-rise buildings that were damaged during the first shock and, as a result, may have responded with lengthened periods (shorter frequencies) putting them in the range of dominant frequencies of the input motions (as shown in Figure 18).
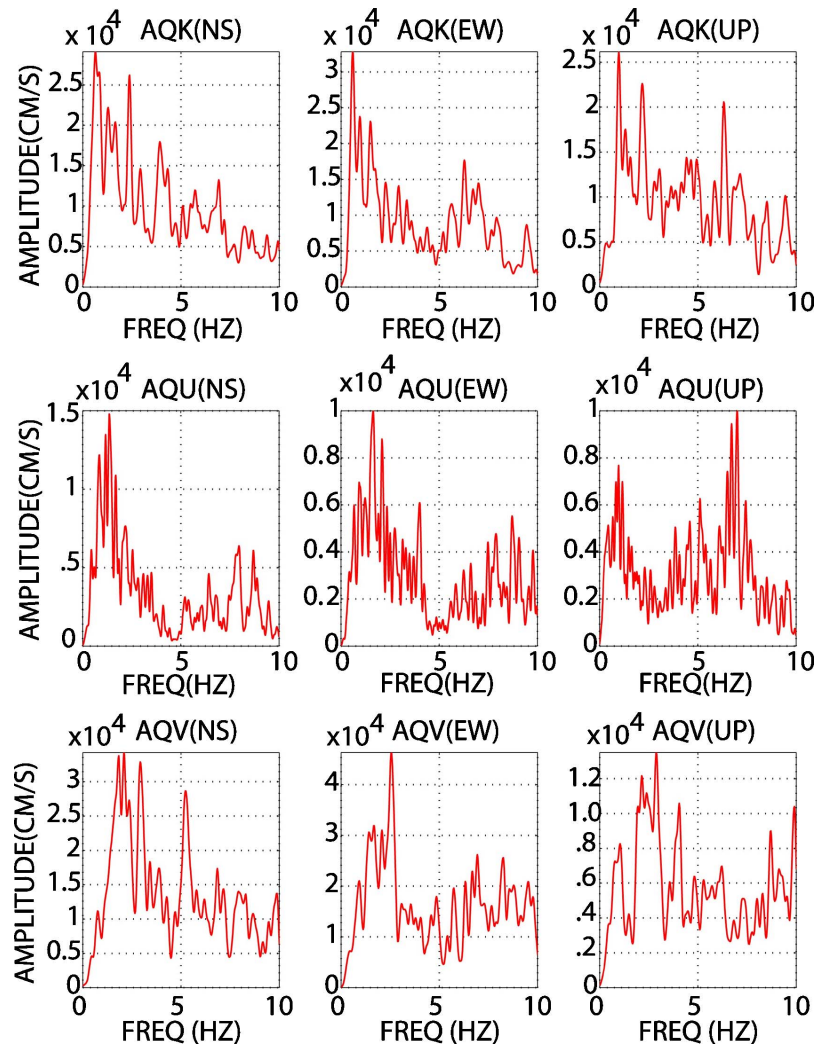
Figure 18. Comparison of amplitude spectra computed from accelerations recorded at AQK, AQU, and AQV.

ELASTIC AND INELASTIC RESPONSE SPECTRA

Analyzing the elastic displacement demand, d, (Figure 19), for the strong motion records not affected by the particular location of the instruments, it is possible to obtain a more realistic description of the seismic demand than the elastic acceleration spectra, compatible with the observed damage (Decanini et al. 2009). In the range between $0 - 1.0$ seconds, the spectral displacements do not exceed 12 cm. Another interesting description of the destructive potential of earthquake ground motions compatible with the damage pattern can be obtained by the inelastic strength demand spectra (Decanini et al. 2009) in
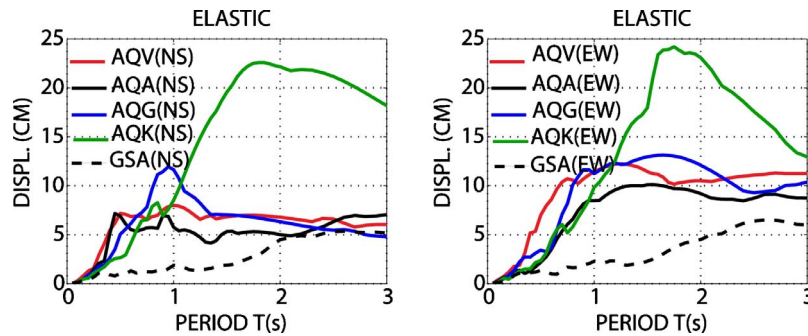
Figure 19. Elastic displacement spectra for five stations.

terms of C_y (i.e., the ratio between maximum base shear and conventional weight of the building, which accounts for dead loads and a fraction of the live loads), described in Figure 20 (for a displacement ductility $\mu=2$). The figure clearly demonstrates that, except for GSA, the inelastic demand ($C_y \sim 0.4-0.8$ g for $T<0.5$ s in the NS direction and $C_y \sim 0.2-0.8$ g in the EW direction) on structures were very high, and for structures not well designed according to the seismic code, the demand far exceeded their capacities.

SHORT NOTE ON TRANSFER FUNCTIONS

Figure 21 shows transfer functions computed from H/V ratios, using Nakamura's (1989) micro-tremor method, of smoothed amplitude spectra for AQK, AQU, and AQV. Clearly, the bands of amplified frequencies are different for the valley (AQV) as compared to AQK and AQU located at the perimeter of L'Aquila. For AQK, a clear amplification band is identified between $\sim 0.4-0.6$ Hz and at ~ 8 Hz. This is consistent with findings of De Luca et al. (2005). For AQU, it is apparent that there are resonances between $1-4$ Hz and between $7.5-10$ Hz—clearly in the range of frequencies for typical one-to-
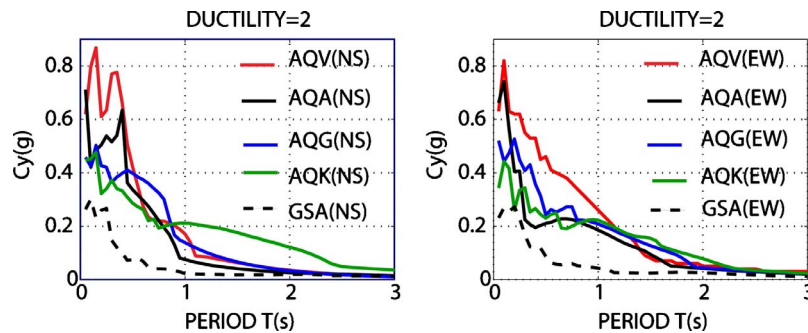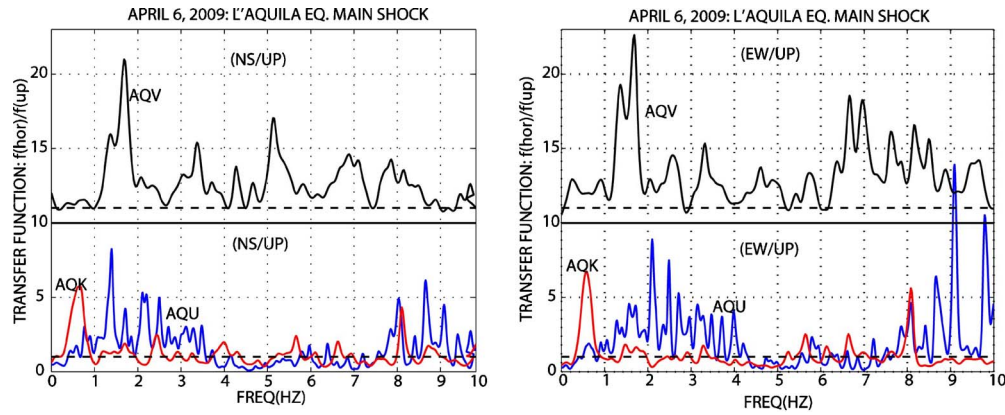

Figure 20. Inelastic strength demand spectra, C_y (g) for displacement ductility=2 (Decanini et al. 2009).

Figure 21. Transfer functions for AQK, AQU, and AQV computed by H/V ratios of amplitude spectra.

eight-story buildings in L'Aquila. Thus, it is fair to state that site responses perhaps played an important role in the behavior and performances of the structures in L'Aquila and the region. In any case, such information should be associated with studies related to the vulnerability characteristics of existing buildings in the area.

STRONG SHAKING DURATION

As demonstrated by the comparative normalized cumulative sum of squared acceleration (which can also be described as Arias Intensity, or comparative energy) plots in Figure 22 for stations AQK, AQU, and AQV, the duration of strong shaking, as indicated by the records is short. Hence, the strong shaking damaged the majority of deficient structures within a couple of cycles rather than sustained/prolonged displacement excursions. If the effective duration had been longer at higher level of accelerations, displacement demands would have been higher. Certainly, the region is capable of generating
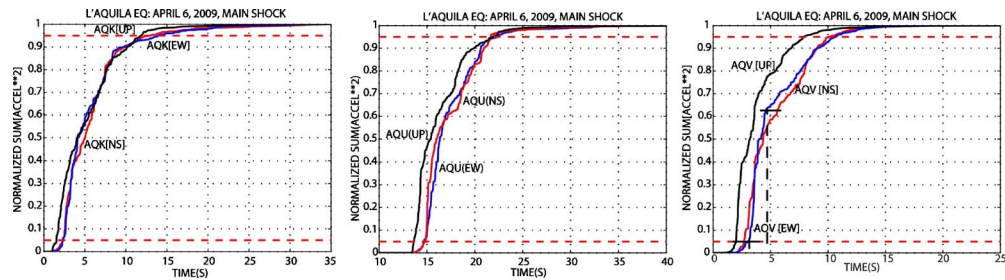
Figure 22. Cumulative sum of squared acceleration at AQK, AQU, and AQV indicate the strong shaking duration (90% of the energy) to be between 3−10 seconds and that 60% of strong shaking occurs within about 3−5 seconds.
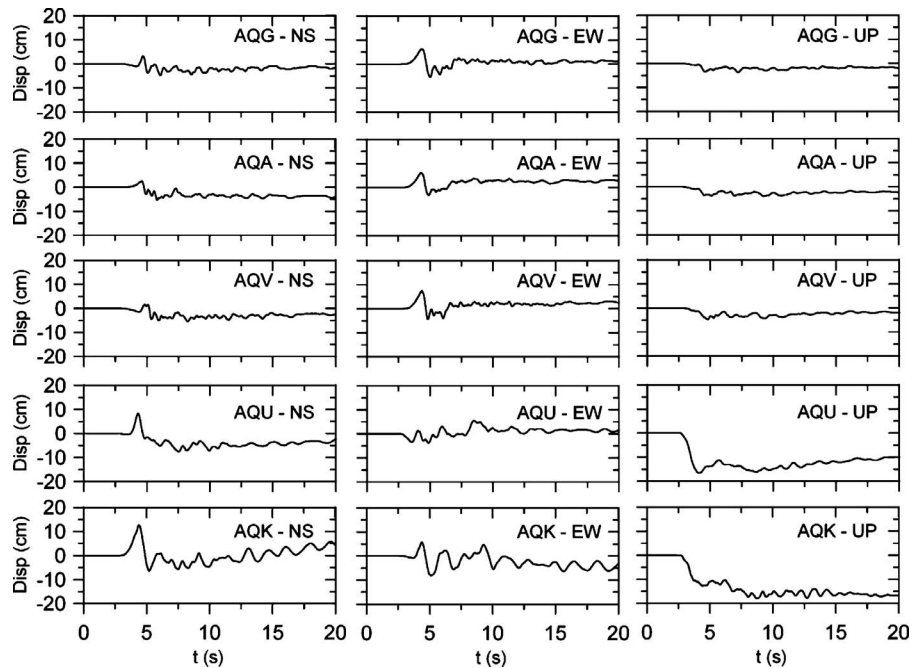
Figure 23. Coherent displacement time series at the Aterno Valley stations (AQG, AQA, AQV) and at L'Aquila stations (AQU, AQK): (a) NS, (b) EW, and (c) UP components. To obtain displacements, acceleration records were processed by a baseline correction technique, consisting of least-squares fitting the velocity time histories by three consecutive line segments, and removing them from velocity (from Paolucci and Smerzini 2010).

larger events (e.g., the $M_w=7.0$ event in 1915). Furthermore, Figure 22 shows that approximately 90% of the energy affected the structures within $3-10$ seconds, and in the case of AQV, 60% of the energy affected the structures within a duration of about 2 seconds or less. Longer-duration shaking would certainly exhibit different statistics on collapsed buildings.

PERMANENT DISPLACEMENTS FROM RECORDS

Because the standard processing procedures of strong motion records for engineering purposes remove the long period signal from the data due to applied acausal filters, it is necessary to analyze the original data if the actual displacement time history is of interest (e.g., Ellsworth et al. 2004). After removing a trend defined by the pre-event data, many of the near-source records for the L'Aquila earthquake can be integrated twice in the time domain to obtain permanent displacements of up to 15 cm in the vertical direction that are in good agreement with the geodetic results (Atzori et al. 2009). Figure 23 shows three component plots of coherent displacement time series at the Aterno Valley stations (AQG, AQA, AQV) and at the L'Aquila stations (AQU, AQK) obtained by Paolucci and Smerzini (2010).

In most cases, permanent displacements of ground motions during earthquakes may adversely affect the fate of those structures built on top or very close to the rupture surface. No such specific occurrences were observed by the authors who participated in reconnaissance surveys of structures following the L'Aquila earthquake. In general, it is difficult to assess how permanent displacements of ground that occur during earthquakes affect vulnerable structures unless the structures are right on top of the surface rupture with permanent displacements (Faccioli et al. 2008).

GROUND MOTION PREDICTION EQUATIONS

Predicting ground motions with ground motion prediction equations (GMPEs) and comparing them to the peak ground accelerations of an earthquake is of particular interest to validate regional design ground-motion levels and to assess the reliability of probabilistic hazard analyses. Therefore, attenuation with the distance of the maximum horizontal ground motion data from the L'Aquila earthquake is compared against predictions using several GMPEs according to two distinctively different but unique "distance" definitions associated with the predictive equations. Table A1 in the Appendix provides the details of the ground motion data of 59 stations utilized for the L'Aquila earthquake comparison. However, in this paper, a total of 58 peak horizontal components of acceleration from the L'Aquila earthquake data set (Table 1) are utilized to make the comparisons. AQM data in Table 1 is excluded due to the considerations discussed above. GMPE comparisons other than those presented here can be found in GEER (2009).

In the first case, the distance definition, called the Joyner-Boore distance definition (R_{JB}) (Boore et al. 1997) is the closest distance from the recording station to the surface projection of the rupture fault plane. Figure 24 compares the PGA (the larger of the horizontal components) of L'Aquila earthquake with two European GMPEs utilizing R_{JB} definition (Sabetta and Pugliese 1987, 1996 [SP96] and Akkar and Bommer 2007 [AB07]). The latter is a prediction equation based on 532 accelerograms from Europe and the Middle East, recorded from 131 earthquakes with moment magnitudes ranging from 5 to 7.6. As can be expected, because of the rupture plane is physically under many of the recording stations as seen in Figure 24 (left), the data from the closest stations falls on an R_{JB} distance of 0 km right at the axis. The data from stations on the hanging wall of the fault are underpredicted even if they are included in the uncertainty bounds of the Akkar and Bommer (AB07) equation (dashed line = ±1 standard deviation). Concerning the data at larger distances, it is interesting to point out that the simple inclusion of an anelastic coefficient (0.005 ×distance) in SP96 (orange curve) fits the data very well. In fact, it is only recently that the availability of high sensitivity digital instruments has made accessible very low ground accelerations recorded at large distances that show the effect of the anelastic attenuation generally not considered in common GMPEs using strong motion data up to distances of 100–200 km.

In the second case, the distance definition used is the closest distance from the recording station to the surface projection of the fault (not the plane; Campbell and Bozorgnia 2008). Fitting this definition, the GMPEs selected are those of Grazier and Kalkan (2007, 2009) and Campbell and Bozorgnia (2008). The GMPEs of Graizer and

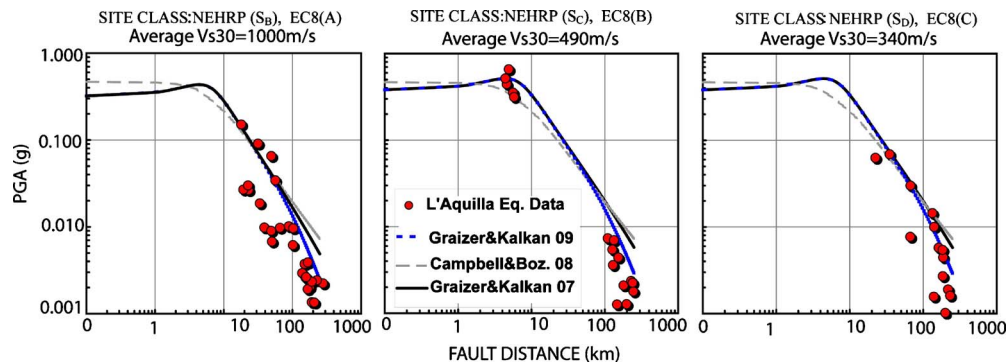(a)   (b)
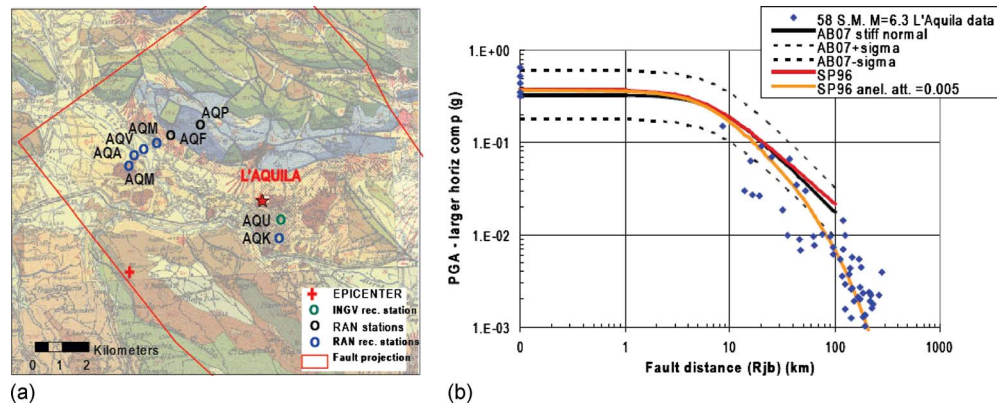
Figure 24. (a) Details of the strong motion stations closest to the epicenter, including the AQU-INGV station, together with the surface projection of the ruptured fault superimposed on the geological map. AQF and AQP only recorded the aftershocks. (b) Comparison of PGA values recorded for the main shock with different attenuations (AB07—Akkar and Bommer 2007, plotted for the case of normal fault and stiff site conditions; SP96—Sabetta and Pugliese 1996) showing as the introduction of an anelastic coefficient=0.005 into Sabetta-Pugliese equation that vastly improves distant data fit (Sabetta et al. 2009)

Kalkan (2007) and Campbell and Bozorgnia (2008) were developed based on the NGA[4] database (Power et al. 2006), and the GMPE of Sabetta and Pugliese is based on an indigenous dataset compiled from Italian earthquakes that occurred prior to 1996.

To facilitate comparisons, the L'Aquila earthquake data set is split into three bins according to generalized site categories as defined in Eurocode (EC8 2004) site classes A, B, and C (corresponding to NEHRP site classes SB, SC, and SD, respectively). As seen in Figure 25, the comparisons with GMPEs indicate an overall good fit to recorded data up to about 100 km from the causative fault. Beyond 100 km, there is notable over-estimation of the recorded data. It is apparent that for all site-categories, recorded data show faster attenuation in the order of R-4 beyond 100 km and slower attenuation in the order of R-1.5 at closer distances. Particularly in this part of Italy, the Q-value of the media ($Q=1/2\xi$, where ξ is damping) is low (or damping is high); hence, ground motion shows faster attenuation as documented by De Luca et al. (2005). Note that fast attenuation is typical for the Western United States with relatively low Q-values, and slow attenuation is characteristic for Eastern United States with higher Q-values. In order to capture such regional differences in the attenuation of seismic radiation, Graizer and Kalkan's (2007) GMPE is adjusted based on the global data to show an average attenuation in the order of R-2.5 beyond 100 km. As shown in Figure 25 for 0 to 100 km distances, the 2007 and 2009 versions produce similar predictions; the difference in prediction is for distances less than 100 km.

Figures 24 and 25 both indicate that in the near field, the near distance definition

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[4] NGA stands for Next Generation Attenuation project (Power et al. 2006)

SITE CLASS:NEHRP (S_B), EC8(A)
Average Vs30=1000m/s

SITE CLASS:NEHRP (S_C), EC8(B)
Average Vs30=490m/s

SITE CLASS:NEHRP (S_D), EC8(C)
Average Vs30=340m/s

- L'Aquilla Eq. Data
- Graizer&Kalkan 09
- Campbell&Boz. 08
- Graizer&Kalkan 07

PGA (g)

FAULT DISTANCE (km)

Figure 25. Comparison of maximum peak horizontal ground acceleration of L'Aquila earthquake with predictions from four GMPEs for EC8 site categories A, B, and C.

($<$10 km) becomes important and shows some of the recorded PGAs above the GMPEs, particularly for the first case. For distances up to 100 km, the recent GMPEs (Sabetta et al. 2009, Grazier and Kalkan 2007) better predict the recorded data.

DISCUSSION OF MOTIONS VS.DAMAGE AND IMPLICATIONS

The following is a summary of categorized discussions of recorded main shock motions and relevant structural characteristics as they pertain to damages observed during this earthquake.

GROUND MOTION CHARACTERISTICS

Although it has been shown that PGA is a poor indicator of the damage potential of earthquake ground motions (Bertero 1992), the amplitudes of strong shaking affecting L'Aquila and other nearby settlements in the region (within a 10-km epicentral distance) exceeded 0.3 g and possibly reached up to 1 g in the case of the Pettino area. As indicated by response spectra, the frequency content of the recorded motions was high, particularly in the range $1-10$ Hz ($0.1-1$ s), which corresponds to the range of fundamental frequencies (period) of most of the inventory of buildings in the affected region. The duration of strong-shaking was short, between $5-10$ seconds. In the case of shaking at the central valley station AQV, 60% of the strong-shaking energy was released within 3 seconds. This is an important characteristic of this earthquake, as it implies that relatively large-amplitude, medium-to-high-frequency shaking affecting the structures was sustained over only a few cycles. Furthermore, velocity time series of records in the near-field and comparative normalized cumulative energy plots together reveal that the most of the seismic input energy from the earthquake source was imparted to structural systems with few intense, double-sided velocity pulses. Also, the dominant frequencies of these strong velocity pulses match the fundamental frequencies of some buildings, thus creating an impact motion and forcing

the structures to dissipate the imparted energy within a short period of time. The performance of any one structure with such input varied according to its vulnerability and, in many cases, the degree of ductility.

GEOLOGY AND SITE ISSUES

As reported following many earthquakes worldwide, amplification and resonance (caused by the synchronized frequency of the site with that of structure) due to geological and/or topographical site response may have played an important role in the fate of some of the buildings, particularly those on the ridges extending from the alluvial fan of L'Aquila towards the valley. However, there are no (main-shock) measurements or data from such areas to corroborate any topographical effect. It is noted that at least two of the significant stations (AQG and AQK) that produced important records during the main shock may have been influenced by topographical effects due to local site conditions. It is possible that soil-structure effects may have also influenced the record at AQK. It is also shown that geological site amplification occurred within frequency bands that are similar to those of the typical building inventory in L'Aquila. Specific microzonation and site response studies are necessary to understand the role of the subsoil, its geometry and the topography on the shaking variation.[5] In particular, it is necessary to incorporate the effect of the calcareous geological formation in the region in the site factors used in the building codes.

STRUCTURAL CHARACTERISTICS

A significant majority of nonductile, non-engineered and unreinforced masonry buildings (including historical structures), and a significant percentage of reinforced concrete buildings with limited ductility and deficient strength due to design and/or construction practices most likely did not have the requisite capacity to resist the level of shaking experienced without damage. Hence, it is possible that during the short-duration, high-frequency and large-amplitude shaking, the majority of the deficient structures were damaged each to some degree (and some pancaked) within only a few cycles. In other words, the shaking motions did not contribute to damage patterns expected from sustained or prolonged large displacement cycles. This is a likely explanation for why so few (approximately two dozen) of the damaged engineered structures collapsed. It is reasonable to speculate that if a larger-magnitude earthquake similar to that in 1915 (M_w 7.0) had occurred, the expected longer duration of strong shaking would probably exhibit different statistics on collapsed buildings as displacement demands would have been higher and a greater percentage of the deficient structures might be expected to collapse. It is strongly stated that infill walls may have played a very significant role in preventing many of the damaged nonductile framed structures from collapsing ("shoring" and/or "diagonal strut" effect) by dissipating the imparted input energy, even though the infill walls themselves may have been damaged. A large amount of infill walls provide additional shear resistance to such buildings, even though the quality of infill is often questionable. However, this positive help of infill walls was sufficient to

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[5] In the earthquake area, such studies have started in October 2009.

prevent many collapses only because of the relatively short duration of strong shaking, that is, a longer duration of shaking could have further deteriorated or completely eliminated the positive effect of infill walls. In addition to some other factors cited, *lack of ductility* in older buildings (historical or otherwise) or newer buildings (but built according to the pre-2003 code) played a significant role in the collapse of, or heavy damage to, a majority of these structures.

In summary, it is reasonable to conclude that in general, it was surprising that many more of the damaged structures did not collapse at such high levels of seismic demands. As mentioned before, this might be attributed to the short duration of strong shaking. If the duration had been longer and at higher levels of accelerations, displacement demands would have been higher, possibly causing many more buildings to collapse. Another way to improve lateral load capacity of the typical buildings in the region (RC-frame with infill walls) is to construct the infill walls with reinforcement integrated with the frame system, effectively turning them into shear walls.

IMPLICATIONS FOR THE UNITED STATES AND MEDITERREANEAN COUNTRIES

The central, eastern, and other parts of United States and all Mediterranean countries have large inventories of deficient (older design and/or nonductile) low-rise (two to four stories), and mid-rise (five to eight stories) RC and masonry buildings in seismically risky areas. It is not unreasonable to conclude that the risk associated with these deficient structures is significant and can be costly, both in terms of human lives and property loss. As many earthquake specialists advise, systematic elimination of such buildings by replacement or, better yet, by retrofit applications can reduce the risk.

It is also reasonable to conclude that the design and construction practice of not using ductile reinforced concrete shear walls (or a combination of walls and frame structural system) in highly seismic areas, rather than continuing the dominant practice of design and construction of the typical reinforced concrete frame system with infill unreinforced masonry walls, may not sufficiently reduce the risk from future earthquake hazards. Seismic risk to RC-framed buildings with masonry infill walls is described in detail, along with appropriate retrofit solutions including the implementation of RC-shear walls in a recent World Housing Encyclopedia publication (Murty et al. 2006). In many other countries with serious seismic hazard (e.g., Chile, Argentina, and the United States), a considerable percentage of the plan areas of buildings are designed with reinforced concrete shear walls. Following the 1999 Izmit, Turkey, earthquake, there have been some proposals for retrofit of RC-framed buildings with masonry infill walls by strategically replacing some of the infill walls with RC shear walls (Sucuoglu et al. 2006). The vulnerability of RC-framed buildings with infill walls was originally related to the cross-sectional areas of lateral force resisting elements (columns and walls) by Shiga et al. (1968) and Ersoy and Tankut (1996). As mentioned previously, Hassan and Sozen (1994) proposed that buildings with lateral force resisting elements of ground floor with approximately 0.35-0.4% of the total building floor area exhibited better performance during earthquakes. Gülkan and Sozen (1999) related vulnerability of reinforced concrete buildings with or without infill walls to column and masonry infill wall

ratios of the total dimensions (area) of a building. Recently, Canbolat et al. (2009) presented results of studies leading to recommendations indicating that approximately 1.5-2% shear wall index (defined as the area of shear wall per story floor area) provides excellent performance and constrains drift ratio- and therefore the damage vulnerability—of a building. Thus, there are many studies that may be used in the assessment of vulnerabilities of suspected deficient buildings.

CONCLUSIONS

The M_w 6.3 earthquake that occurred on 6 April 2009 close to L'Aquila in central Italy caused loss of lives and property and will adversely affect the economy of the region for several years. The extent of damage can be attributed both to (a) the existence of a large inventory of structures with deficient capacity and ductility and (b) shaking that exceeded design levels and was characterized by significant, short-duration velocity pulses with dominant frequencies similar to the fundamental frequencies of typical buildings in the region. The town of L'Aquila was severely affected, as the majority of its structures were damaged to some degree. Despite this tragedy, L'Aquila was fortunate that the extent of damage was limited by the short duration of strong shaking.

The area has experienced larger earthquakes in the past and will experience more in the future. In Italy, as well as in the United States and other earthquake-prone countries, future larger earthquakes with long-duration pulses pose a serious level of risk to the deficient structures and, in turn, people's lives. Remedial actions must be taken seriously. In addition, potentially adverse affects of near-source events must be addressed in future earthquake design code revisions.

During the process of recovery and reconstruction, it is important to adopt better design and construction practices, as well as tested retrofit techniques, in order to achieve improved performances of the buildings and other structures during future earthquakes in this region of Italy and elsewhere. This includes the consideration of the potentially adverse affects that might result from prolonged shaking in larger earthquakes. One of the many desirable applications that can be used to improve the performances of new buildings or in retrofitting of deficient existing buildings is to increase the percentage of the area of lateral force-resisting elements, as discussed in this paper.

ACKNOWLEDGMENTS

APPENDIX A

Table A1. Database of strong round motion records from M6.3 L'Aquilla earthquake (Data source: http://itaca.mi.ingv.it/ItacaNet/. Measured and/or estimated V_{S30} data available from: http://www.geerassociation.org/GEER_Post%20EQ%20Reports/Italy_2009/italy_2009_index.html; note: AQM data is not used due to considerations explained in the text).

No.	Station Code	Location	Lat.	Long.	R_{JB} (km)	R_{epi} (km)	Max PHA (g)	Max PHV (cm/s)	EC8 Site class
1	ANT	ANTRODOCO	42.418	13.079	19.3	23	0.026	2.47	A
2	AQA	L'QUILA-V.ATERNO-F.ATERNO	42.376	13.339	0	4.6	0.444	32.03	B
3	AQG	L'AQUILA-V.ATERNO-COLLE DE GRILLI	42.373	13.337	0	4.4	0.517	35.54	B
4	AQK	L'AQUILA-PARCHEGGIO	42.345	13.401	0	5.6	0.354	36.21	B
5	AQM	V.ATERNO-IL MORO	42.379	13.349	0	5.2	>1 g	N/A	A
6	AQU	L'AQUILLA CASTELLO	42.354	13.405	0	5.8	0.315	35	B
7	AQV	L'AQUILA-V.ATERNO-CENTRO VALLE	42.377	13.344	0	4.9	0.659	42.83	B
8	ASS	ASSISI	43.075	12.604	96.5	101.7	0.006	0.43	A
9	AVL	AVELLINO	40.923	14.787	185.7	198	0.001	0.38	B
10	AVZ	AVEZZANO	42.027	13.426	25.1	34.9	0.069	11.28	C
11	BBN	BIBBIENA	43.748	11.821	194.5	199.5	0.001	0.24	C
12	BDT	BADIA TEDALDA	43.707	12.188	172.8	178.8	0.002	0.38	A
13	BNE	BENEVENTO	41.128	14.785	167.9	180.2	0.002	0.68	B
14	BOJ	BOJANO	41.484	14.472	121.1	133.4	0.014	3.33	C
15	CAN	CANDELA	41.203	15.475	217.6	217.6	0.002	0.33	C
16	CDS	CASTEL DI SANGRO	41.787	14.112	76.2	88.4	0.010	1.72	A
17	CER	CERIGNOLA	41.260	15.910	232	245.2	0.002	0.452	B
18	CHT	CHIETI	42.37	14.148	52.2	67	0.030	7.91	C
19	CLN	CELANO	42.085	13.521	20	31.6	0.091	6.64	A
20	CMB	CAMPOBASSO	41.563	14.652	126.5	138.7	0.003	1.3	A
21	CMR	CASTELMAURO	41.833	14.712	112.9	126.6	0.005	0.74	B
22	CNM	CASALNUOVO MONTEROTARO	41.618	15.105	153.1	166.6	0.002	0.84	A
23	CSO1	CARSOLI 1	42.10	13.088	31.7	33.5	0.019	2.29	A
24	CSS	CASSINO	41.486	13.823	91.1	102.6	0.010	1.64	A
25	CTL	CATTOLICA	43.955	12.736	178.8	186.7	0.004	0.76	C

Table A1. (cont.)

No.	Station Code	Location	Lat.	Long.	R_{JB} (km)	R_{epi} (km)	Max PHA (g)	Max PHV (cm/s)	EC8 Site class
26	FMG	FIAMIGNANO	42.268	13.117	16.6	19.3	0.027	2.61	A
27	FOR	FORLI'	44.199	12.042	225.6	232.3	0.002	0.63	C
28	GNL	GENZANO DI LUCANIA	40.843	16.033	266.5	279	0.002	0.57	A
29	GSA	GRAN SASSO (Assergi)	42.421	13.519	8.6	18	0.151	9.84	A
30	GSG	GRAN SASSO (Lab. INFN galleria)	42.46	13.55	13.7	22.6	0.030	3.04	A
31	ISR	ISERNIA	41.611	14.236	97.3	109.7	0.007	0.78	B
32	LSS	LEONESSA	42.558	12.969	35.6	39	0.010	0.83	A
33	MMP1	MOMPEO 1	42.249	12.748	45.9	49.1	0.009	0.89	A
34	MNG	MONTE S. ANGELO	41.704	15.958	217	228.4	0.002	0.35	B
35	MNN	MANFREDONIA	41.634	15.911	212.4	226.8	0.002	3.53	A
36	MTR	MONTEREALE	42.524	13.245	15.9	22.4	0.063	3.53	C
37	NAP	NAPOLI Ovest	40.799	14.18	173.1	184.6	0.003	5.86	C
38	ORC	ORTUCCHIO	41.954	13.642	37.3	49.3	0.065	5.86	A
39	PDM	PIEDIMONTE MATESE	41.355	14.385	127.1	139.4	0.002	0.3	C
40	PIC	PIANCASTAGNAIO	42.85	11.685	143	146.7	0.001	0.3	B
41	PTF	PETRELLA TIFERNINA	41.696	14.702	120.4	133.4	0.007	1.31	B
42	RIC	RICCIA	41.483	14.838	144.1	156.3	0.003	0.56	A
43	SBC	SUBIACO	41.913	13.106	46.6	50.4	0.007	1.26	A
44	SCM	S. CROCE DI MAGLIANO	41.711	14.984	139.2	152.9	0.004	0.8	B
45	SCP	SERRACAPRIOLA	41.807	15.165	147.8	162.1	0.006	1.19	C
46	SDG	S. GIOVANNI ROTONDO	41.709	15.733	195.6	191.6	0.001	0.2	A
47	SEP	S. ELIA A PIANISI	41.625	14.88	137.1	150.2	0.004	0.83	A
48	SNM	SAN MARINO	43.934	12.449	184.7	191.9	0.002	0.7	A
49	SNS	SANZA	40.243	15.550	284.9	167.9	0.004	0.74	A
50	SPC	SPOLETO (cantina)	42.743	12.74	63.2	66.7	0.008	0.69	C
51	SPO	SPOLETO	42.734	123.741	62.6	65.9	0.010	0.81	A
52	SSR	S. SEVERO	41.691	15.374	169	183.1	0.005	1.25	C

Table A1. (cont.)

No.	Station Code	Location	Lat.	Long.	R_{JB} (km)	R_{epi} (km)	Max PHA (g)	Max PHV (cm/s)	EC8 Site class
53	STL	SATRIANO DI LUUCANIA	40.541	15.642	277	277	0.001	0.27	A
54	STN	STURNO	41.018	15.112	195.6	207.8	0.001	0.29	A
55	SUL	SULMONA	42.089	13.934	43.4	56.4	0.034	3.73	A
56	TLS	TELESE TERME	41.222	14.53	146.2	158.5	0.003	0.56	A
57	TMO	TERMOLI	41.989	14.975	126	140.6	0.010	2.88	C
58	VIE	VIESTE	41.877	16.165	224.2	239	0.002	0.48	B
59	VRP	VAIRANO PATENORA	41.333	14.132	117.5	129.4	0.004	0.81	B

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