Learning from Earthquakes

The M_w 6.3 Abruzzo, Italy, Earthquake of April 6, 2009

From April 17-24, a team made up of representatives of the Earthquake Engineering Research Institute, the Applied Technology Council, and the Pacific Earthquake Engineering Research Center investigated the effects of the Abruzzo earthquake. The team was led by Paolo Bazzurro, AIR Worldwide Corp., San Francisco, and included David Alexander, CESPRO, University of Florence; Paolo Clemente, ENEA Casaccia Research Centre, Rome; Mary Comerio, Dept. of Architecture, UC Berkeley (PEER); Adriano De Sortis, Italian Dept. of Civil Protection, Rome; Filip Filippou, Dept. of Civil Engineering, UC Berkeley (PEER); Agostino Goretti, Italian Dept. of Civil Protection, Rome; Mersedeh Jorjani, architectural conservator, San Francisco (ATC); Fabrizio Mollaioli, Dept. of Structural and Geotechnical Engineering, University of Rome La Sapienza; Khalid Mosalam, Dept. of Civil Engineering, UC Berkeley (PEER); H. John Price, Curry Price Court, San Diego (ATC); and Marko Schotanus, Rutherford & Chekene, San Francisco. A separate team from the Geo-engineering Extreme Events Reconnaissance Association (GEER), led by Jonathan Stewart of UCLA, also contributed to this report.

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Introduction

On Monday April 6, 2009 at 3:32 a.m. local time, an M_w 6.3 earthquake with shallow focal depth (10 km) struck central Italy in the vicinity of L'Aquila, a city of about 73,000 people that is the capital of the Abruzzo region (Figure 1).

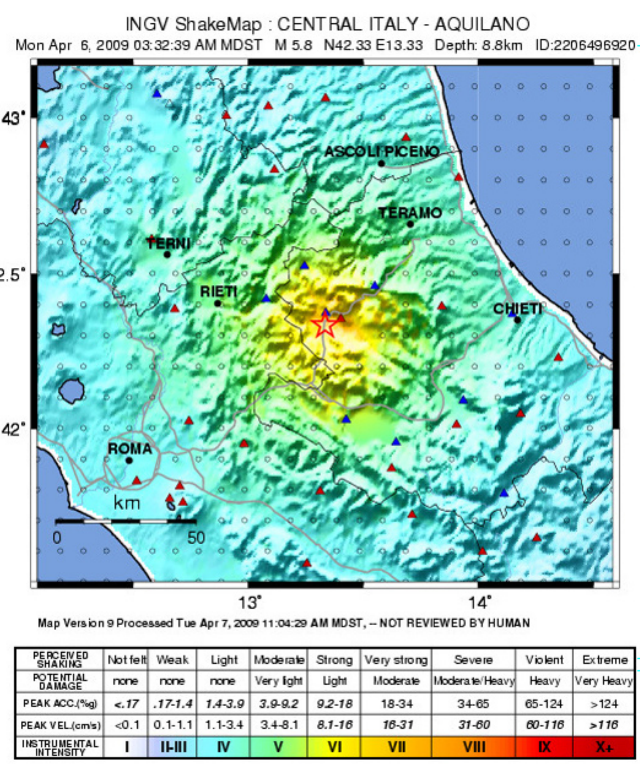

Figure 1. *The epicenter of the Abruzzo event.*

The earthquake killed 305 people, injured 1,500, destroyed or damaged an estimated 10,000-15,000 buildings, prompted the temporary evacuation of 70,000-80,000 residents, and left more than 24,000 homeless. This event was the strongest of a sequence that started a few months earlier and numbered 23 earthquakes of M_w>4 between 03/30/09 and 04/23/09 (Figure 2), including an M_w 5.6 on 04/07 and an M_w 5.4 on 04/09.

A total of 81 municipalities were affected by the earthquake, and 49 of them were in the Prime Ministerial Decree regarding damage of Mercalli-Cancani-Sieberg (MCS) intensities VI-X. (Note that in this range of intensities, the Modified Mercalli Intensity [MMI], more widely used in the U.S., can be computed as $I_{MMI} = 5/6\ I_{MCS}$, as reported by Decanini et al., 1995).

The population of L'Aquila includes 14 surrounding boroughs such as Onna, Paganica, and Tempera (see Figure 3). The combined population of the 48 other towns listed in the

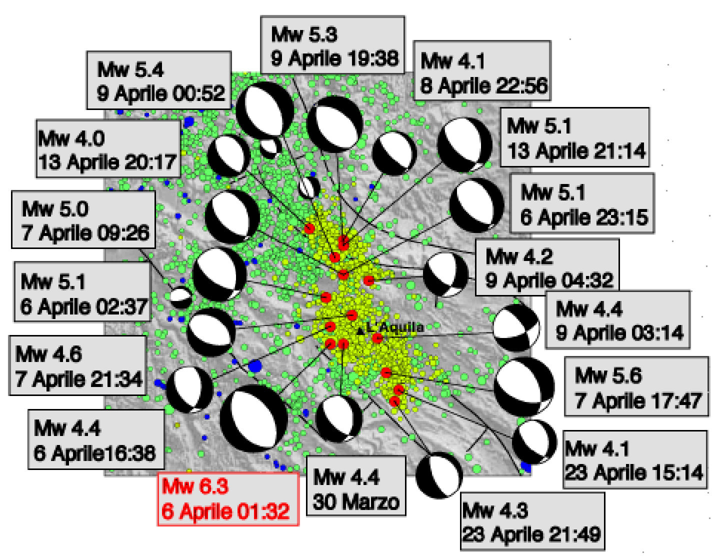

Figure 2. *Characteristics of 23 earthquakes above M_w4 from 3/30 to 4/23 (Italian National Institute of Geophysics and Vulcanology).*

Figure 3. *The L'Aquila area and the locations of fatalities.*

official earthquake damage declaration is 60,352. The majority range in size from 1,000 to 3,000 people, with two larger towns of 5,000 and 8,500 inhabitants.

The earthquake struck when most people were sleeping. The locations of the 305 deaths can be seen in Figure 3. The fatalities were concentrated in the 20-29 and over-70 age groups, though that does not reflect the more balanced demographics of L'Aquila province. The peak in the 20-29 group was due to the collapse of a student dormitory in downtown L'Aquila.

Many of the region's cultural sites were badly damaged or destroyed, including Romanesque churches, palazzi, and other monuments dating from the Middle Ages and Renaissance. The historic centers of villages in the Aterno River valley southwest of L'Aquila — Onna, Paganica, and Castelnuovo — were essentially obliterated, with shaking intensities of up to X on the MCS Scale.

Conversely, damage did not exceed MCS intensity VI nearly anywhere to the northwest of L'Aquila. This southeastward elongation of the damage pattern probably reflects a combination of rupture directivity and seismic litostratigraphic amplification effects.

Seismotectonic and Geological Setting and Historical Seismicity

The city of L'Aquila is located in the central part of the Apennine chain, a thrust-belt that represents a margin of a plate deformed during continental collision between the African plate (to which it belongs) and the Euroasian plate that took place in the Cenozoic 65 million years ago (Cavinato and De Celles, 1999; Devoti et al., 2008). The Apennines belong to a geodynamic system that migrates from the Tyrrhenian to the Adriatic area (from W to E) in response to the flexural retreat and subsequent sinking of the Apulia platform. This unit is being subducted westward beneath the Apennines (Doglioni et al., 1990, 1991). The city is located on a tectonic basin bounded by predominantly NW-SE-striking and SW-dipping active normal faults (Blumetti, 1995; Bagnaia et al., 1996). Downtown L'Aquila is set on a fluvial terrace that forms the left bank of the Aterno River (De Luca et al., 2005). The elevation of the terrace reaches 900 m above mean sea level (asl) in the northeastern part of the city and slopes down to 675 m asl in the southwest direction. The terrace ends at the Aterno River, which flows 50 m below. The alluvial deposits constituting the terrace are lower Quaternary in age, and are composed of breccias with limestone boulders and clasts in a marly matrix. Clast dimensions can range from centimeters to meters.

This kind of deposit is common in the Abruzzo region and may be related to catastrophic alluvial events associated with landslides (Blumetti, 1995). The deposits were studied by Demageout (1965), who named them "megabrecce." The megabrecce represents a well-defined geological unit with flat top and bottom surfaces and a thickness of some tens of meters, lying on lacustrine sediments composed mainly of silty and sandy layers and minor gravel beds. The lacustrine sediments reach their maximum thickness (around 250 m) in the center of L'Aquila. In contrast, in the Aterno River valley north of L'Aquila, the thickness of the sediments is never greater than 100 m.

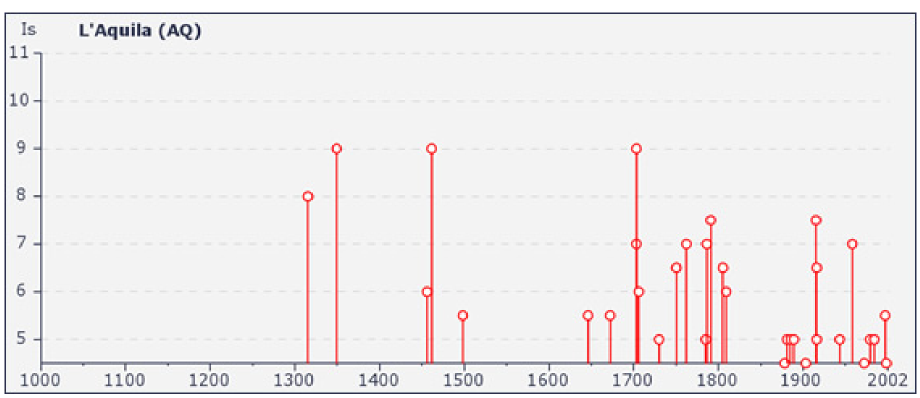

Figure 4. *Historical MCS macroseismic intensity of the major events near L'Aquila since 1300.*

N.	Codice record	Codice stazione acc.	Località	Provincia	Regione	Lat N	Long E	PGA (cm/s^2)	Distanza epicentrale (Km)
1	GX066	aqv	L'Aquila - V. Aterno - Centro Valle	L'Aquila	ABRUZZO	42,377	13,344	662,599	4,80
2	FA030	aqg	L'Aquila - V. Aterno - Colle Grilli	L'Aquila	ABRUZZO	42,373	13,337	504,921	4,30
3	CU104	aqa	L'Aquila - V. Aterno - F. Aterno	L'Aquila	ABRUZZO	42,376	13,339	478,000	5,80
4	AM043	aqk	Aquil PARK ing.	L'Aquila	ABRUZZO	42,345	13,401	366,285	5,60
5	EF021	gsa	GRAN SASSO (Assergi)	L'Aquila	ABRUZZO	42,421	13,519	148,862	18,00

Table 1. *Details from five stations with epicentral distance less than 20 km (source: Italian Dept. of Civil Protection).*

Figure 4 shows the earthquakes that have struck the city of L'Aquila and the villages around it since 1300 (Stucchi et al., 2007; Rovida et al., 2009). L'Aquila has been severely damaged at least five times in the last 700 years, specifically in 1315 (M_w≈6.7), 1349 (M_w≈6.5), 1461 (M_w≈6.5), 1703 (M_w≈6.7), and 1915 (M_w≈7.0). The 1461 event shows a damage distribution similar to that of the April 6 earthquake, although it is shifted to the east by a few km.

Ground Motion Records

Fifty-six of the approximately 300 digital strong-motion stations operated by Italian Strong Motion Net work (RAN) managed by the Italian Department of Civil Protection (DPC) recorded the main shock. In addition, 142 broad-band stations recorded it. Fourteen stations are in the Abruzzo region, while the remaining ones are scattered in the Apennines mostly NW and SE of L'Aquila. This makes the Abruzzo M_w 6.3 event one of the best recorded earthquakes caused by a normal fault mechanism. Five stations, all on the hanging wall of the rupture, were located within 10 km of the epicenters, and all recorded a horizontal peak ground acceleration exceeding 0.35g (Table 1). One station (AQM, not included in the table) recorded 1g or more in the vertical and one horizontal direction, but went off scale above 1g in the second horizontal direction. Its recordings are still subject to study; they have not yet been released.

The stations AQG, AQK, and AQM are on rock or stiff high-shear-wave-velocity (Vs) material, while AQA and AQV are on recent alluvium. Preliminary comparisons of ground motion intensity measures (IMs) from record ings to prediction equations performed by the GEER team show that high-frequency IMs attenuated more rapidly with distance than is predicted by most empirical relations. This faster attenuation is consistent with a recently published modification of the next generation of attenuation equations based only on Italian data (Scasserra et al., 2009).

The 5%-damped spectra of the two horizontal directions produced by USGS for the stations in Table 1 have shown, with the exception of the AQK station, that the ground shaking had mostly a high-frequency content (Figure 5). The ground motion had also relatively short duration: 95% of the energy was released in 10 seconds or less. Finally, unprocessed data obtained from many stations show permanent displacements of up to 15 cm.

Geotechnical Aspects

The Geoengineering Extreme Events Reconnaissance Association (GEER) dispatched a team to the affected region within four days of the main shock. Their field survey revealed no surface fault rupture, although they observed numerous incidents of ground deformation. It is possible that these were associated with co-seismic slip on shallow

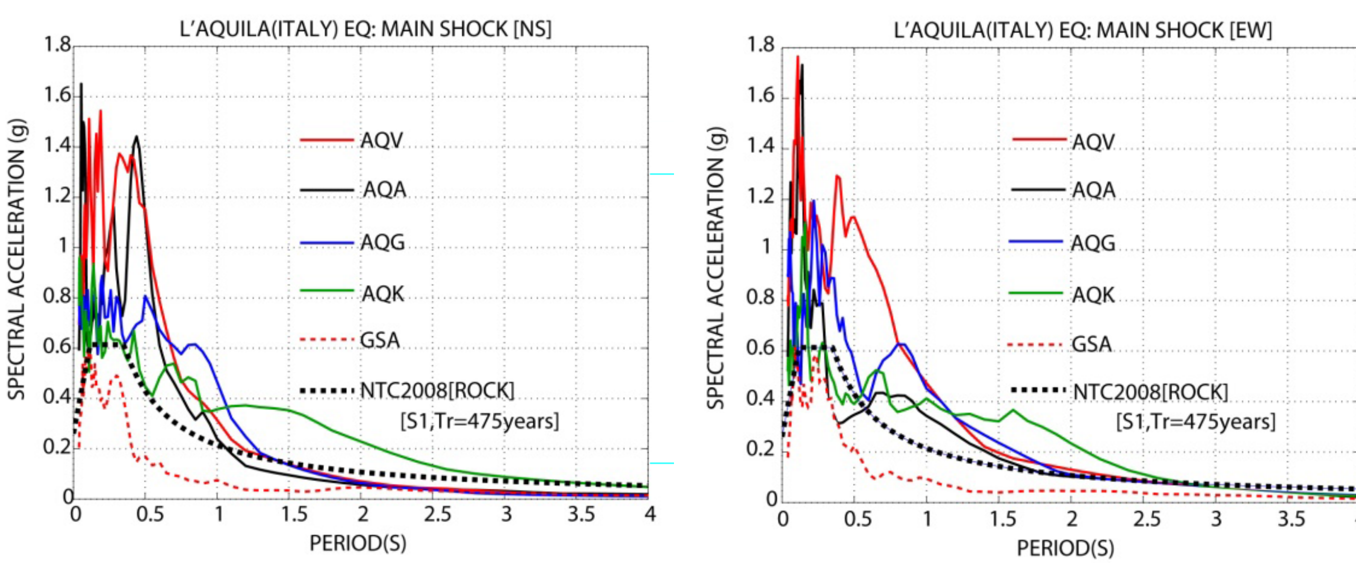

Figure 5. *Response spectra for 5% damping for the 5 stations in Table 1 that recorded >0.1 g and comparison with 2008 Italian Code Spectrum.*

Figure 6. *Devastation of poor-quality buildings in Paganica.*

faults not associated with the main event.

Damage patterns illustrate strong effects of site conditions. On a local scale within suburban areas of L'Aquila, GEER's structure-to-structure mapping showed higher concentrations of damage in relatively modern reinforced concrete structures located on Holocene sediments than in similar neighboring structures on Pleistocene sediments.

On a broader scale, high damage levels were seen in villages founded at least partly on relatively young sediments (Onna, Castelnuovo); only light damage was visible in neighboring villages on bedrock materials (Tussio, Monticchio).

Incidents of ground failure involved disaggregated rock falls, seismic compression of poorly compacted fills, minor deformations of levees and flood control embankments, and slumping/spreading of sediments around Lake Sinizzo. Earth and concrete dams at several reservoirs in the strongly shaken region performed well. Earth-retaining structures also generally performed well, although some failures were documented.

Historic Masonry Buildings

In the Abruzzo region, as in most of Italy, the historic city centers are the core of the built environment, accounting for 20% of larger cities like L'Aquila and 50% of smaller towns. In the L'Aquila area, building began in the 13th century and continued to the modern era. The older unreinforced masonry (URM) dwellings in the historic centers (usually 2-3 stories) are built with stone and mortar walls; more recent URM structures show a mixed use of rubble-stone and clay bricks, and in some instances concrete blocks. In general, masonry buildings suffered a great amount of damage.

The team surveyed buildings in L'Aquila and approximately 20 surrounding towns (of the 49 cities and towns included in the ministerial damage decree). While L'Aquila had dramatic damage to late medieval, Romanesque, and Renaissance buildings and artwork, more widespread extensive damage was seen in smaller towns such as Onna, Paganica, and Castelnuovo, where more than 50% of the historic centers were damaged beyond repair (see Figure 6). In other towns, such as Barisciano, Santo Stefano, and Monticchio, approximately 20-25% of the buildings in the center suffered extensive damage. The difference between the damage levels observed at locations that are very close to one another, such as Onna and Monticchio, and that have URM buildings of the same quality and characteristics, is most likely due to site amplification effects (see the GEER report for details).

Typical damage observed in L'Aquila consisted of generalized cracking of the masonry walls, especially between openings and in corners, leading to loss of the superficial plaster and sometimes causing localized collapses in poorly reinforced cornices and above window lintels. Complete collapses of masonry structures in the historic center of L'Aquila were rare, although the severe damage observed in many rubble stone walls might trigger demolition of some this building stock. Firefighter squads and the survey team also observed failures of floor slabs inside buildings, which rendered the structure unsalvageable. These floor collapses might have been triggered by out-of-plane deformation of walls and subsequent loss of support for the floor beams.

The superior performance of many of the masonry buildings in L'Aquila can also be attributed to the better quality of material (e.g., bigger size, squared stones) and construction that could be afforded by the richer families that have lived there historically. Several masonry buildings observed within the historic center of L'Aquila had cross-ties (*catene*) situated adjacent and parallel to the walls, with the purpose of limiting the out-of-plane deformation of the buildings. These structures generally performed well, displaying only minor cracking in their walls and corners.

The majority of buildings in the countryside villages of lower in-

Figure 7. *Detail of 18th century wall-strengthening system, where no ties connect the beam to the wall.*

Figure 8. *Collapse of a masonry building in Tempera with concrete ring beam retrofit.*

come populations used a construction technique (called *a sacco*) that made them very vulnerable to earthquake damage. In this type of building, the gravity loads are carried by thick unreinforced stone with two outer wythes, often of rounded stones that are poorly connected, if at all, by a limited number of bond stones. Space between the two outer wythes is often filled with an inner core of smaller rubble masonry, poorly consolidated and aggregated by a mixture of lime or mud mortar. This results in walls with limited vertical and lateral capacity because of the presence of voids between the stone masonry and the scarcity of effective continuity between the inner and outer wythes. Cross ties were also sometimes used in these buildings with limited effectiveness because the deteriorated, poorly maintained walls lacked sufficient strength to carry the concentrated out-of-plane load imposed by the ties during the shaking.

After the last major earthquake in the region in 1703, attempts were made to strengthen masonry walls by inserting a large (approximately 20 cm diameter) timber into the wall with wood or iron ties through the perpendicular wall. In Paganica, we saw numerous examples of this approach, where the first story was built after the 1703 earthquake using the timber-and-ties technique, but 2nd and 3rd floors were added in the 19th century without ties, as the technique was forgotten (Figure 7).

Another interesting retrofit from the modern era was the use of a concrete ring beam to stiffen the wall and prevent collapse. This was used

Figure 9. *(a) Santa Maria del Suffragio, built after 1703, and (b) Santa Maria di Paganica, both in L'Aquila, lost the roof and cupola.*

Figure 10. *Roof and cupola collapse in the Santa Maria di Collemaggio Abbey in L'Aquila. The reinforced concrete ring beam did not prevent the collapse of the cupola.*

on a number of churches (Figure 10). Unfortunately, this system proved to be ineffective, and many structures, such as the building in Figure 8, collapsed. The additional mass of the beam, the inconsistency between the deformation of the beam and that of the walls, and the lack of positive connection between the beam and the masonry walls above and below are reasons that were brought up to explain the generally poor results of this retrofit technique.

Many churches in the region experienced partial failures of their walls and domes, fall of architectural elements, out-of-plane wall failures, and cracking of bell towers and corners (Figures 9 and 10). Some particular cases of interest were the Chiesa di Santa Maria del Presepe in Paganica that suffered very little damage in contrast with the rest of the town, probably due to the reinforcing corner plates and the proper anchorage of roof trusses into the walls. The Palazzo Dragonetti, built at the end of the 18th century and recently restored as a high-end hotel, had its corners heavily reinforced with cross-ties and showed no damage. A church near Monticchio had its front façade separate from the lateral walls due the inability of the wood connection beams to keep the structure in place; however, other parts of the façade tied with iron rods performed well, showing no separation of the structural elements.

Reinforced Concrete Buildings

The post-WWII residential buildings are of reinforced concrete construction, typically 2-4 stories tall, but reaching up to eight in some cases. Most are multifamily condominiums, and some have offices or retail stores at the ground floor. For building design purposes, L'Aquila was considered seismic after the 1915 Avezzano earthquake, and buildings have been designed according to seismic provisions ever since.

In the more modern building codes issued in 1975 and revised in 1996, the province of L'Aquila was assigned to seismic zone 2, and structures built up to 2003 were designed for a horizontal acceleration of 0.23g; after the application of appropriate code coefficients, that translated into a design base shear of about 7% of the sum of dead loads plus one third of the design live loads. No specific provisions for ductility were included. The new code adopted in 2003 provides only a minor increase of the design peak ground acceleration (0.25g) in L'Aquila, but includes strict guidelines to ensure that adequate ductility is achieved. Very few buildings in the area, however, have been designed according to the new code.

The older RC buildings in the region use smooth reinforcing bars, unconventional lap splices, and in some cases, poorer quality construction materials. The frames are almost always designed with no consideration for the layout of masonry infill walls both in plan and elevation, as these are considered to be nonstructural elements, and their exclusion is thought to lead to conservative design. The framing is filled in with one or two wythes of hollow clay or concrete blocks, and sometimes finished with wrap-around clay brick facades or stucco. Partitions are of thin hollow clay blocks.

We found widespread damage to exterior infill walls and interior partitions, varying from small cracks to collapse along with minor or no damage to structural elements. Several buildings completely lost their masonry infill walls at lower stories (Figure 11). This kind of damage extended to newer build-

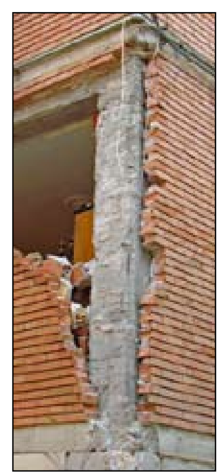

Figure 11a/b. *Typical damage to infill walls.*

Figure 12. *Collapse of part of the Duca D'Abruzzi Hotel caused by a soft-story mechanism. The far part of the building was saved by a seismic separation joint.*

ings, including structures that have been recently completed. In L'Aquila, the team also observed about 15 older low- to mid-rise apartment buildings and one large hotel that suffered dramatic failures (Figure 12), generally due to a soft-story at the first or second story. At all the collapse sites, the team noticed the remains of column-beam connections that showed insufficient transversal reinforcement in the form of 6 mm diameter stirrups, at a spacing of 25cm or more. In some cases, there was also poor distribution of fine aggregates and cement in the concrete, with a very porous core of disconnected larger aggregates. Short overlap of longitudinal rebar connecting columns between the upper and lower stories, short anchorage lengths of the longitudinal beam reinforcement, and smooth rebars may have been responsible for the reduced structural strength and ductility of these buildings.

In Pettino, northwest of L'Aquila, there were several pockets of reinforced concrete structures that suffered significant damage. Among them were two soft-story collapses (Figure 13) and a large modern concrete structure with shear failure in several columns of its moment-resisting frame and the shear wall of its elevator core at the lower story (Figure 14). Since several columns remained intact, it is possible that torsional effects contributed to the unusual shear failure distribution, as the building is "L"-shaped in plan. Detail deficiencies included insufficient column ties (i.e., excessive spacing and small section, which results in inadequate confinement), lack of cross ties, and splices with inadequate length.

In summary, reinforced concrete buildings in the L'Aquila region behaved, on average, fairly well, considering the limited seismic design requirements and the severe ground shaking, often in exceedance of the design level. From the perspective of the repair cost, however, reinforced concrete buildings showed higher losses due to widespread extensive damage to masonry infill walls and internal partition walls (Figure 15).

Public Buildings

Hospitals: The EERI team inspected the San Salvatore Hospital, the

Figure 13. *Soft-story collapse in Pettino. Two of four almost identical structures collapsed.*

Figure 14. *Core shear wall with extensive structural damage and failure in a modern RC building in Pettino.*

Figure 15. *The interior of the City Planning Offices in L'Aquila. Note that the building exterior has very minor detectable damage.*

main hospital in the L'Aquila province located in Coppito. This hospital, which has 13 wings constructed from 1972-2000 to a 1967-era "intermediate" seismic design, attracted a great deal of attention in the media because it was shut down some hours after the earthquake, likely because of damage to a few concrete columns in three of its many buildings (Figure 16). Patients were transferred elsewhere. Nonstructural damage was relatively moderate and limited. About 70%-80% of the hospital is expected to be re-opened over the period June-October. The hospital staff reported neither deaths nor injuries due to earthquake damage at this site. Hospital emergency utilities operated as planned.

Aside from structural column damage in three aforementioned relatively confined zones, the team could locate no other significant damage to the concrete frame. The nonstructural infill masonry likely contributed to resisting the earthquake lateral forces and limited the frame deformation.

Schools: The damage level in schools was varied. The EERI team was able to inspect the exterior and the interior of six schools in the area. The Pettino Elementary School, a two-story reinforced concrete frame with infill brick walls completed in 1994, was seriously damaged and reached the verge of partial collapse (Figure 17). The damaged pillars on the ground floor showed nonductile detailing in the beam-column joints, the minimal confining reinforcement, and smooth rebars. A separation in the concrete between the top of the pillars and the upper beams was also evident.

On the other hand, the middle school in Pettino, a two-story reinforced concrete frame with infill brick walls completed in the 1980s, had a small amount of nonstructural damage. Similarly, the elementary school in Pianola, a two-story reinforced concrete frame with infill brick walls built at the end of the 1990s, showed no structural damage. An internal nonstructural wall collapsed and a water heater fell down.

The team surveyed two older masonry schools. The first, the elementary school in Coppito (two stories of about 5 m each, built in 1930), had been strengthened in 2003-04 by adding micro-piles in the foundation. The school showed moderate damage on the second story at one of the corners, but not on a first story where metal crossties were present in the original design.

Figure 16. *Column damage at hospital entry structure; no tie reinforcement is evident.*

Figure 17. *Extensive damage to the elementary school in Pettino.*

Figure 18. *Partial collapse of the roof.*

The second elementary school in L'Aquila, an old (1400-1700) poor-quality masonry building formerly used as the hospital, was seriously damaged and its roof partially collapsed.

Industrial Structures

The industrial building construction in L'Aquila is similar to that found in the United States: precast concrete buildings with precast panels, reinforced frames with concrete block walls, and steel or light metal frames with precast panel walls. The damage observed was generally concentrated in nonstructural elements (e.g., partitions and ceiling tiles) and contents, although some structural damage to beams and columns was observed.

Figure 19. *Extensive damage at one silo.*

This was the case at the two-story reinforced concrete frame Vibac chemical facility close to Paganica, engineered in 2003 and constructed in 2006. The exterior was primarily glass window wall with hollow clay tile infill at the stair core and the back of the building, adjacent to a one-story precast warehouse. We observed multiple column shear failures, rupture of the column tie reinforcement spaced at 20 cm, cracking and falling of the hollow clay tile infill, and collapse of the window wall glass.

In the warehouse, a precast girder collapsed along with one span of roof slab (Figure 18). There did not appear to be any positive connection of the precast girders to the exterior precast frame, and the exterior wall appeared bowed, allowing the girder to unseat.

At a manufacturing plant in the same facility we observed three tall steel silos storing polypropylene beads that suffered damage. The three silos that were full during the earthquake either collapsed or suffered extensive damage (Figure 19). The silos pounded on the adjacent precast warehouse, partially crushing the concrete wall and leaving an imprint of impact. The silos also crumpled at their bases. The undamaged sections are being salvaged and reused.

Lifelines

Highways A24 and A25, connecting the Tyrrhenian and Adriatic coasts of Italy, run through the area affected by the earthquake. The A24 is in many parts an elevated dual carriageway, consisting of simply supported single-span bridge segments on reinforced concrete piers of varying height (Figure 20a). The A24 and A25 were closed for inspection following the earthquake, but reopened to passenger vehicles a few days later. In several locations, spans moved off their bearings (Figure 20b/c); these stretches of highway were closed for repair. During our visit, both highways had been re-opened to all traffic, except for a local part of highway A24 in L'Aquila, where repairs were still in progress and traffic in both directions was detoured.

The only collapsed bridge structure was over the Aterno River along a secondary road to Fossa. The bridge was of reinforced concrete construction with three continuous spans. The collapse of the bridge

Figure 20. *(a) Reinforced concrete highway viaduct that suffered movement of (b, c) bearings and misalignment of columns.*

was likely induced by failure of the columns; we found a bridge of the same design and vintage which also showed evidence of damage in the column hinge. Slight damage to a few other bridges was also reported.

A number of regional and provincial roads were partially closed, mainly as a result of earthquake-induced land and rock slides and settlements. Driving on provincial route 38, from L'Aquila to Avezzano, we passed a few closed roads and were deviated at Ovindoli. Driving to Fossa, we noted various locations where the steep embankment had slid down, though was still retained by the wire protection. Close to Fossa, we found the road closed because of rock slides. Work was in progress during our visit to remove rock falls, restore embankments, and repair paving.

The railways crossing the area affected by the earthquake were inspected immediately after the event, and most were reopened in time to have a minimal impact on service (given the early hour of the earthquake). All local lines were reopened by the end of the day, except for the one track from Rome to Sulmona, which required repairs due to a minor landslide. Full service was active by April 9, three days after the earthquake.

The airport at Pescara maintained regular service during and after the event. The national air traffic authority ENAV closed the air space in a radius of 25 miles around the epicenter to an altitude of 10,000 ft. to provide uninterrupted access to helicopters supporting emergency rescue operations.

Utility networks for water, electricity and phone services were all briefly interrupted by the earthquake, but damage was localized. All services were fully functional within a day after minor repairs and reconfigurations. Natural gas services to areas with significant damage were interrupted upon request of the fire department as a safety precaution. Gas provider ENEL successively checked over 250 miles of pipes for damage. Natural gas and electricity remained off in areas of severe damage, like downtown L'Aquila and Onna, and several individual users remain disconnected because of severe damage to their buildings. Gas and electricity provider ENEL contributed to emergency response and temporary housing operations by providing mobile gas canisters to the field hospital and the central command center of the Department of Civil Protection, and electrical service to shelters and tent camps.

The most important damage to the water system was the pipe break in the aqueduct from the Gran Sasso, the main water supply of the area. A high pressure water main broke at the crossing of the Paganica fault, which experienced a co-seismic movement in the main event. There were also a number of pipe breaks in the distribution system, and many had to be repaired in order to provide water to emergency shelters and temporary accommodations. A pipe break was reported as far away as Pescara on the Adriatic coast.

Phone services were only briefly interrupted because of power failure. Problems were typically solved by putting emergency generators into service. Our team heavily depended on mobile phones for communication and coordination, and did not find any irregularities in available services.

Emergency Management and Building Inspections

Given that the local prefecture building collapsed during the quake, the Central Coordination Center of the emergency was run by the Department of Civil Protection from the campus of the local police academy school in Coppito, outside L'Aquila. Local management was delegated to seven different centers in the affected area.

By April 8, a total of 2,250 firefighters, 1,500 army personnel, 2,000 policemen, and more than 1,000 technical employees of the Abruzzo Regional office were working in the region, as were 3,000 volunteers. By then, 31 tent cities had been put up to house 17,772 homeless people, and 171 hotels on the Adriatic coast were allocated to host an additional 10,000. Field hospitals were also installed to provide first emergency aid. The facilities for the care and housing of homeless residents increased over time, with about 1,700 private residences in the region opened for displaced people.

On April 14, the first temporary school was opened in a tent city at Poggio Picenze. On April 20, the University of L'Aquila reopened in a temporary structure at Coppito. As of April 27, about 66,000 people were in temporary shelters, 36,000 in 5700 tents, and 30,000 in 433 hotels and 1,600 private dwellings. On April 29, the mayor of L'Aquila declared that the people whose dwellings were declared safe for occupancy could go back.

The inspections of private houses started two days after the quake on April 8, after the teams had completed public buildings such as hospitals and schools, and commercial and industrial sites. The systematic inspections of all the residential buildings started from the less damaged neighborhoods and moved gradually to the most damaged ones. Areas farther from the epicenter are inspected only upon request.

About 1,500 inspectors were deployed every day to evaluate about 1,000 buildings daily. Each squad comprised three building professionals, at the beginning from the public sector, but later from the private sector as well. Inspections were also carried out by engineers from other EU countries (Spain, Portugal, Slovenia, Germany, France, and Greece) sent by the Monitoring Information Center of the European Community. These teams were also joined by a group of technicians sent by the Ministry of the Russian Federation for Affairs of Civil Defense, Emergencies and Disaster Relief (EMERCOM).

As of May 2, about 24,000 buildings had been inspected outside of the most damaged areas that were subjected to mandatory evacuation. About 65% of the buildings were green tagged (ready for occupancy) and 27% were red tagged (unsafe for occupancy). The historic centers of L'Aquila and other villages most damaged by the quake had not yet been inspected because of the high risk.

Societal Impacts

Analyses of worldwide patterns of earthquake casualties suggest that 50-90% of deaths occur between midnight and 6 a.m. Studies in central America and Turkey highlight the importance of vernacular housing as a risk in nocturnal earthquakes or, indeed, whenever people are likely to be at home (Glass et al., 1977; Angus, 1997; Rodriguez 2005). That is equally true in Italy, where the only buildings more vulnerable to collapse (and on occasion fully occupied) are ecclesiastical ones.

In this earthquake, the overall death/injury ratio of 0.20 was relatively low, as 0.33 has been hypothesized for medium-to-large earthquakes. The case fatality rates of 0.17 overall and 0.60 for serious and critical (hospitalized) injuries are low in the first case and high in the second, as the ratio of serious to all injuries was only 0.13, which is somewhat small by comparison with similar earthquakes elsewhere (commonly it might be 0.15-0.25).

The risk of injury and death was greatly increased by the collapse of URM walls, either as coherent slabs or in fragments; separation of URM walls from roofs, with collapse of cornices and upper masonry; detachment of roofs; ejection of infill walls in RC buildings; and detachment and collapse of the corners of URM buildings.

Given the complexity of failure patterns in vernacular housing, it is reasonable to suppose that no single self-protective behavior would have been appropriate under all conditions. In heavily damaged buildings, there was little to protect people from crush injuries or burial by dust and rubble. Few cavities were present in the rubble of collapsed buildings. Running into the street clearly put people significantly at risk from falling masonry or the collapse of stairways. In any case, rapid egress was made difficult by doors that jammed as a result of racking distortion.

The societal effects of any disaster can only really be assessed after more than three weeks have passed, but some immediate observations can be made. As of May 3, 2009, over 65,000 people, approximately half of the population of L'Aquila and surrounding areas, were still in temporary housing (tent cities, hotels on the Adriatic coast, and private residences).

Nora Habed, a psychologist with SIPEM (Italian Emergency Psychologists), whose organization works with the Department of Civil Protection, has been counseling people living in hotels on the coast. She has found that many people would prefer to stay in tent cities rather than in a hotel far away because they would have more contact with their neighbors and could do things such as cooking. Furthermore, some people are having difficulties in hotels, since they have to abide by hotel rules and restrictions such as curfew times. It is especially difficult for the elderly to adapt to this type of life. As time passes and a large portion of the population is still without permanent housing, people will increasingly feel the precariousness of their lives.

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