OBSERVATIONS FROM THE MAGNITUDE 6.3 L'AQUILA EARTHQUAKE

05.2009

EDITOR'S NOTE: Before dawn on Monday, April 6, a destructive M6.3 earthquake occurred in the Abruzzo region of central Italy, becoming the deadliest earthquake to strike Italy since the 1980 Irpinia earthquake. Two weeks later, AIR engineers were on site surveying the damage. AIR's director of engineering analysis and research, Dr. Paolo Bazzurro, was asked by the California-based Earthquake Engineering Research Institute (EERI) and Pacific Engineering Research Institute (PEER) to lead their joint reconnaissance team. He was joined by AIR senior research engineer Dr. Guillermo Franco. From London, AIR research associate and engineering seismologist Dr. John Alarcon joined the Earthquake Engineering Field Investigation Team (EEFIT). This article presents their preliminary findings.

By Drs. Paolo Bazzurro, Guillermo Franco and John Alarcon

INTRODUCTION

On Monday April 6, 2009, a moderate earthquake struck central Italy. Although the geographic extent of damage was limited, the magnitude 6.3 earthquake was felt as far north as Bologna and as far south as Napoli—nearly 160 km (100 mi) from the epicenter.

One day after the earthquake, AIR estimated that insured losses would likely range between €200 million and €400 million. Although insured losses will be limited as a result of low take-up rates in the region, physical damage was extensive. In addition to the historic center of L'Aquila—the largest city nearest the epicenter and capital of the Abruzzo region—several surrounding towns and villages were heavily affected, including Onna, Castelnuovo, Paganica, and San Gregorio.

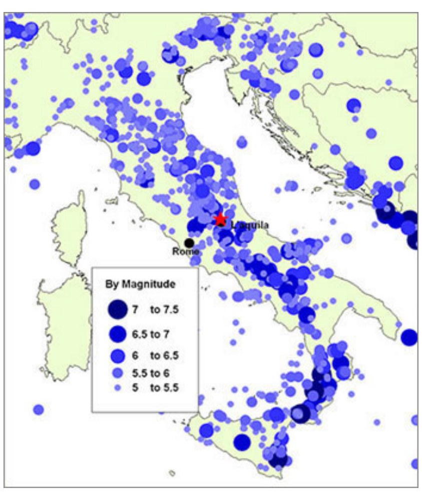

Figure 1. Epicentral location of the April 6th L'Aquila earthquake (denoted by the red star) and historical seismicity since 217 BC. Source: AIR

Figure 2 shows a comparison between ground motion observations published by Italy's Office of Civil Protection and ground motion for the event as estimated by AIR's Italy earthquake model. Near-source recordings can be rare, but are critically important for purposes of damage and loss estimation.

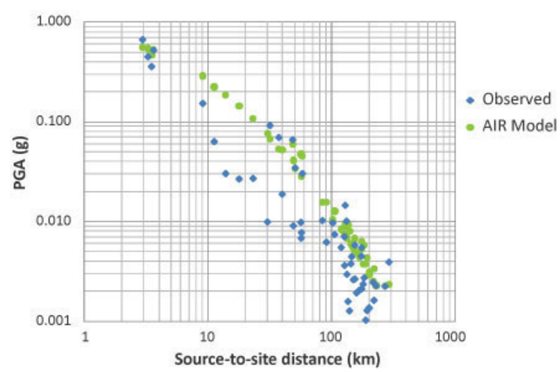

Figure 2. Comparison between AIR Modeled Mean Ground Motions and Observed Ground Motions

It is worth noting that one of the instruments in the epicentral region recorded peak ground acceleration (PGA) of 0.67g.[1] Yet until 2003, buildings in L'Aquila and its province were considered to be in a moderate "Class 2" seismic zone, which prescribes only that buildings be able to withstand a peak horizontal acceleration of 0.23g. The newer building code released in 2003 and revised in 2008 require design PGA of 0.25g. In either case, given the observed ground motions, the implications for the levels of damage the survey teams would see were clear.

AIR engineers spent one week traveling throughout the affected region, collecting and synthesizing information on structural and non-structural damage. Their routes are shown in Figure 3. Most of the towns visited lay along the valley formed by the Aterno River, though forays were also made into the more mountainous terrain to the west and nearer the epicenter.

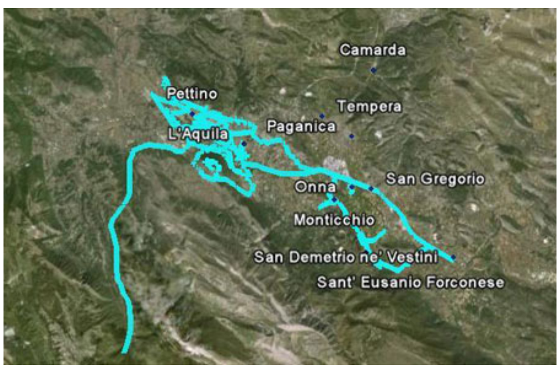

Figure 3. Blue outline represents the area visited by the survey teams.

CONSEQUENCES OF THE QUAKE

The shallow focal depth (10 km) undoubtedly exacerbated the damage from this earthquake, which killed nearly 300 people, destroyed or damaged an estimated 10,000 to 15,000 buildings, prompted at least the temporary evacuation of 70,000 to 80,000 residents and left more than 24,000 homeless. 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 eras. Plans for reconstruction are underway, but early indications suggest that the government's overstretched budget may restrict their ability to fully retrofit many of the older buildings in the region as they are repaired. Instead, damaged buildings would be restored to their pre-earthquake condition. This would be a departure from past practice in the 1970s, 1980s, and 1990s when the government paid for full retrofitting or partial strengthening.

DAMAGE WITHIN L'AQUILA

Unreinforced Masonry

Not surprisingly, the most significant damage within L'Aquila was to the unreinforced masonry (URM) structures of L'Aquila's historic center—many of them more than 100 years old, but not likely to predate 1703 when the last major earthquake almost leveled L'Aquila. URM is characterized by a limited ability to resist the lateral loads imposed by ground shaking.

Facades of masonry structures still standing showed cracks varying in severity, from loss of plaster to separation of the walls from the structure (Figure 4). In this latter case, the structural integrity of the wall, the load-bearing system, is compromised and such buildings will likely be demolished. In isolated cases, the collapse of masonry structures in the old center of L'Aquila was complete. Partial structural collapses of walls or cornices were more frequent.

It should be said that not all URM buildings are the same. L'Aquila, in comparison with the surrounding villages, is and always has been relatively wealthy and the houses—even masonry ones—are, on average, constructed with much better materials and building practices. This has prevented the widepread devastation seen in countryside villages, such as Onna, Paganica, and Catelnuovo, and as discussed in more detail below.

Figure 4. Severe cracks compromise the structural integrity of the wall. Source: AIR

Masonry structures that displayed cross-ties (catena in Italian) as in Figure 5, showed a much better resistance, provided that the lateral walls were properly reinforced.

Figure 5. Effective mitigation devices include cross-ties ("catena" in Italian). Source: AIR

However, in some cases, although the building seemed to be largely intact from the outside, the inside revealed devastation (Figure 6).

Figure 6. From the exterior, this URM building looked relatively unscathed; the interior (on the right) revealed otherwise. Source: AIR

Reinforced Concrete

The large majority of reinforced concrete (RC) buildings fared well considering they were subjected to a ground motion equal to or greater than that for which they were originally designed. However, in older building code specifications, column-beam connections were allowed to be designed with smooth rebar that provide insufficient bonding with the concrete. The consequences are shown in Figure 7. Some failed connections also displayed widely-spaced small-diameter stirrups, which cannot prevent the buckling of longitudinal rebar in columns. Together, these were the cause of most of the RC collapses that the team observed in the field, such as those shown in Figure 8.

Figure 7. Smooth rebar allowed under older code provide insufficient bonding with the surrounding concrete. Source: AIR

Figure 8. Total and partial collapses of older RC buildings in L'Aquila. The collapse of the university dormitory on the right resulted in the deaths of eight students. Source: AIR

Perhaps one of the most publicized collapses was that of a wing of a university dormitory built in the 1970s—again likely the result of shoddy construction.

Figure 9 shows dramatic pancake collapses of the third onto the second story of two RC buildings due to the failure of all the beam-column connections (as described above). Note the balconies, which are now one on top of the other. In the photo on the right, note the identical building behind, which experienced damage at the first floor but not at the second.

Figure 9. Pancake collapse due to beam-column connection failure. Source: AIR and Paolo Clemente (EERI team)

Pounding—a phenomenon in which two adjacent buildings hit each other during an earthquake because they are too close together and have different natural periods of vibration—was another damage mechanism encountered during the survey. Figure 10 shows a textbook example of pounding. The roof of the 2-story building hit the column of the adjacent 4-story structure causing the failure of all the columns at that level. Note that the first, third and the fourth story essentially show no damage.

Figure 10. Classic example of damage due to pounding. Source: AIR

Modern RC frame buildings (i.e., those designed after 2003 when the last building code was issued) fared much better than those built in the 1960s through the 1980s. They generally suffered no exterior damage or perhaps minor to moderate damage to exterior infill walls and interior partitions. Figure 11 shows a typical example of shear cracking to brick infill; while this building will be costly to repair, there is no damage to the underlying concrete frame.

Figure 11. Reinforced concrete buildings designed after the most recent code (2003) fared much better than their older counterparts. Source: AIR

NORTH OF L'AQUILA

In the town of Pettino, 3 km (1.86 mi) north of L'Aquila, the survey team found several instances of both pancake collapses and soft-story effects. In one cluster of four almost identical buildings, two collapsed as a result of soft-story failure and two survived—a stark example of the uncertainty that must be taken into account when modeling building vulnerability. Figure 12 shows one of the collapsed buildings, whose columns on the ground floor, which was used for parking, failed—a classic example of soft-story failure. While such buildings can certainly be designed to withstand ground shaking, in this case, the ground-floor column-beam connections displayed insufficient stirrup reinforcement (large spacing and small diameter) and short anchorage lengths of the beam longitudinal rebar in the column.

In order to avoid soft story effects, Eurocode does not allow differences in the rigidities of the frame (beams and columns) between adjacent stories to be larger than 25%. However, most of the soft story failures seen in Abruzzo were the result not of differences in the frame, but rather as a result of the ground floor having open bays and the floor above having infill walls. Eurocode does not specify directly that infill masonry walls must be taken into consideration during the rigidity analysis, nor does it specify how such consideration might be undertaken.

Figure 12. Soft-story failures were observed in the town of Pettino, which sits on soft soils. Source: AIR

EAST AND SOUTHEAST OF L'AQUILA

Many of the towns and villages surrounding L'Aquila have historically been quite poor. Houses here are typically built with poor materials and no craftsmanship—and suffer significant damage or collapse at much lower levels of ground motion than the upper-scale URM buildings in L'Aquila.

Onna, located about 7 km (4.3 mi) southeast of L'Aquila and entirely on alluvial soils, suffered the heaviest damage of any town visited, with collapse or partial collapse of a large proportion of its masonry structures (Figure 13). Three weeks after the earthquake, when these photos were taken, the entire population of the town remained under evacuation orders.

Figure 13. Partial and total collapse of masonry structures in Onna. Source: AIR

Notably, a recently-built school in Onna performed extremely well, with no apparent damage to the exterior (Figure 14). It took the collapse of a school in the Molise earthquake in 2002, which resulted in 26 of the 28 fatalities from that earthquake, to prompt the imposition of much stricter codes in the construction of schools in Italy. The school in Onna provided proof of the efficacy of the new code.

Figure 14. Newly built school in Onna with no evident damage; structures on the opposite side of the street suffered partial or complete collapse. Source: AIR

At Barisciano, the town furthest from L'Aquila that was surveyed, the proportion of masonry structures that partially or completely collapsed was significantly lower than that observed in Onna. Even the most vulnerable construction types, such as the mixed masonry building shown in Figure 15 showed slight or no damage.

Figure 15. Three-story mixed masonry building reinforced with cross-ties in Barisciano appears to be intact. Source: AIR

There were exceptions, however. Figure 16 shows the almost total collapse of an old two-story unreinforced masonry structure, also in Barisciano.

Figure 16. Collapse of a two-story masonry house in Barisciano; the corner of the two-story structure at the far left is shown again in Figure 6. Source: AIR

WEST AND NORTHWEST OF L'AQUILA

In contrast to the damage observed in towns along the Aterno River valley to the southeast of L'Aquila, towns to the northwest experienced significantly less damage. In Coppito, for example, just 5 km (3.1 mi) from L'Aquila, observed damage levels were similar to those in Barisciano, located some 16 km (9.9 mi) distant. Small commercial establishments were open and operating under a normal business schedule. In Preturo, about 9 km (5.6 mi) from L'Aquila, the observed collapse rate for masonry structures was quite low. This asymmetric distribution of damage north and south of the epicenter will undoubtedly provide seismologists with insight into the physical characteristics of the earthquake itself.

INDUSTRIAL DAMAGE

Industrial facilities in the region, which are dominated by RC construction, generally sustained little or no structural damage, but a moderate degree of cracking of infill walls. Figure 17 shows the partial or complete collapse of steel silos.

According to a local engineer, about 20% of all industrial facilities around L'Aquila sustained at least some degree of mostly non-structural damage. Still, despite the limited nature of the damage, most industrial activity around L'Aquila had ceased due to a lack of manpower (primarily as a result of evacuations) or to reparations and testing of machinery and equipment. One manager of a chemical facility mentioned that, while his building was intact, operations would remain shut down until all of the sensitive machinery was tested and recalibrated. The implication was that the company may not have been covered for losses stemming from business interruption.

Figure 17. Complete collapse of two steel silos (located were the empty spaces are) containing polypropylene beads and partial collapse of a third. Parts of the collapsed silos were being stored in the yard to be salvaged and reused. Source: AIR

DAMAGE TO INFRASTRUCTURE

Damage to infrastructure included the collapse of a 0.9 m (2.9 feet) diameter high-pressure water supply pipeline near the town of Paganica. The rupture triggered a landslide and subsequent mud flow (Figure 18), although none of the nearby residential structures was affected.

Figure 18. Landslide caused by the rupture of a water supply pipe. Source: AIR

Cracks were observed on the piling of a 30 m (98 ft) long masonry bridge located at the southwest edge of L'Aquila (not shown). Another short bridge near the town of Fossa completely collapsed (photo on the right in Figure 19), while a large reinforced concrete bridge in L'Aquila was closed due to the displacement of one of its beams on the supporting pier (left in Figure 19).

Figure 19. Damage to bridges in and around L'Aquila. Source: AIR

Many spans of the viaduct of the highway A24 in L'Aquila were lifted off from the bearing pads on top of the piers resulting, in a misalignment. The part of the highway was still closed to traffic when the team surveyed the area.

Figure 20. Spans of L'Aquila's viaduct were lifted off and misaligned with supporting piers. Source: Paolo Clemente (EERI team)

Ground failure was also observed, in some cases resulting in damage and closure of local roadways.

Figure 21. Instances of ground failure in and around L'Aquila. Source: AIR

CONCLUSION

By leading or collaborating with the survey teams from organizations such as EERI, PEER and EEFIT, AIR engineers gained access to otherwise restricted areas, enabling the unhindered study of the L'Aquila earthquake's impact on Italy's unique and historically important building inventory, and the efficacy of mitigation efforts and building codes. In most cases, their observations were in line with expectations—and in line with damage and loss estimates produced by the AIR earthquake model for Italy. Other cases, such as the observed damage to some modern RC buildings, will surely provide fodder for future investigation. While lawmakers grapple with the financial implications of rebuilding to current code, some property owners will undoubtedly take steps to improve the seismic performance of their buildings on their own. Mitigative devices such as tie-rods or horizontal ring bands can help mitigate the impact of future earthquakes—which will undoubtedly recur in this seismically active region of Italy.

Figure 22. AIR's Dr. Paolo Bazzurro (left), who led the EERI reconnaissance team, makes the acquaintance of a local firefighter. Permission to enter L'Aquila's "red zone" had to be granted by the Department of Civil Protection, but even then the teams had to be accompanied by a firefighter or other emergency responder.

1 A STATION IN THE TOWN OF PETTINO RECORDED 1G OR MORE IN THE VERTICAL AND ONE OF THE HORIZONTAL DIRECTIONS BUT WENT OFF SCALE ABOVE 1G IN THE SECOND HORIZONTAL DIRECTION. ITS RECORDINGS ARE STILL SUBJECT TO STUDY AND THEY HAVE NOT YET BEEN RELEASED.

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