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QUICK RESPONSE REPORT

VULNERABILITY OF REINFORCED CONCRETE FRAME BUILDINGS AND THEIR OCCUPANTS IN THE 2009 L'AQUILA, ITALY EARTHQUAKE

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ABSTRACT

Reinforced concrete (RC) buildings—particularly mid-rise, multi-family condominium structures—experienced significant damage in the 2009 L'Aquila, Italy, earthquake. The most frequent type of damage consisted of cracking and, in some cases, failure of nonstructural masonry infill walls. Some structures also exhibited column cracking, spalling, shear failure, and even collapse. Fieldwork conducted three to four weeks after the earthquake was used to collect data about 483 RC frame buildings in the city of L'Aquila. This data included information about building location, characteristics, damage, and post-earthquake loss of functionality. These results show the damage state is correlated to building height, building usage, elevation irregularities in strength and stiffness, and the estimated peak ground acceleration at each location. In addition, census data for the L'Aquila population and building stock were obtained from the Italian National Institute of Statistics and used to estimate the broader impacts of this earthquake on RC buildings in L'Aquila and their occupants. This study shows an estimated 38 percent of L'Aquila residents living in RC structures experienced moderate or heavy damage to their homes. Occupants of older high-rise condominiums in areas immediately north and west of the historic city center were particularly impacted. Damage to RC buildings also led to significant disruption of the community and social fabric, leading to the temporary or permanent closure of government offices, small businesses, restaurants, churches, and schools.

INTRODUCTION

The earthquake that struck L'Aquila, Italy, at 3:32 a.m. on April 6, 2009, had a magnitude (M_w) of 6.3. Its epicenter was approximately 6 km (3.72 miles) from the city of L'Aquila (Camata et al. 2009). Significant damage occurred in L'Aquila, which has a population of 72,550 (Istituto nazionale di statistica 2008), and more than 20 neighboring towns, killing 305 people and injuring at least 1,500 (Camata et al. 2009; Rossetto et al. 2009). In addition, it is estimated that 70,000 to 80,000 residents of L'Aquila and the surrounding towns were temporarily evacuated from their homes and between 24,000 and 34,000 people are now homeless (Rossetto et al. 2009; Bazzurro et al. 2009). After the earthquake, the Italian government housed displaced people in tent camps in L'Aquila and surrounding areas, as well as in hotels on Italy's Adriatic coast (Rossetto et al. 2009).

Masonry structures in L'Aquila's historic center and surrounding villages experienced the most serious damage, including failures of connections between walls, floors, and roofs; out-of-plane wall collapses, and shear failure (diagonal cracking) of wall piers (Camata et al. 2009; Bazzurro et al. 2009). Collapses of masonry homes caused most of the fatalities and many historic monuments were severely damaged or destroyed (Camata et al. 2009; Bazzurro et al. 2009). The other prevalent building type, rein-

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forced concrete (RC) structures, experienced major nonstructural damage and—in a limited number of buildings—significant structural damage. The most dramatic RC building failure was the multi-story section collapse of a five-story L'Aquila University dormitory, which caused a number of casualties (Rossetto et al. 2009; Verderame et al. 2009). A wing of the Duca D'abruzzi Hotel also collapsed (Rossetto et al. 2009; Stewart et al. 2009). Another instance of high profile RC damage included the shear failure of columns at the region's primary hospital, San Salvatore, which was temporarily closed (although some activities continued in a tent outside the building) (Camata et al. 2009; Rossetto et al. 2009; Bazzurro et al. 2009; Stewart et al. 2009). Damage to other strategic structures, such as the masonry building used for police headquarters, was also significant (Camata 2009). Infrastructure systems such as bridges, roads, and gas and water pipelines experienced localized failures (Rossetto et al. 2009; Bazzurro et al. 2009).

This study examines the vulnerability of RC frame buildings and their occupants in the L'Aquila earthquake. We look specifically at *physical vulnerability*—defined as "threat to physical structures and infrastructures" (National Research Council 2006)—in damage patterns of RC frame buildings according to building characteristics and location. We also examine the post-earthquake impacts of inadequate seismic resistance in RC frame buildings on the city's building stock, critical community buildings, and building occupants. This analysis links physical vulnerability associated with RC frames with *social vulnerability*—defined as "the threat to well-being of human populations," including "the relative potential for harm and social disruption to subpopulations of societies" (National Research Council 2006). Understanding who is vulnerable in deficient RC buildings is critical to recognizing barriers and opportunities in the development of programs to retrofit or safely rebuild RC frame buildings. L'Aquila provides an important case study, because RC frame buildings dominate residential and commercial construction in urban areas in Italy today, and their construction, usage, and deficiencies are characteristic of buildings throughout the seismically active northern Mediterranean region.

SEISMIC DESIGN OF RC BUILDINGS IN L'AQUILA

RC frame buildings constructed without seismic design and detailing principles or with poor quality workmanship are known to be vulnerable to earthquake-induced damage and collapse. As with U.S. codes, Italian seismic design codes have been revised in the last 30 years. These changes reflect improved understanding of the importance of avoiding brittle failure modes through ductile detailing of reinforcement and capacity design methods. Although some instructions for seismic design were added to 1970s Italian reinforced concrete design codes, the 1984 version was the first real seismic code requiring ductile detailing of reinforcement (Camata 2009). Other principles of seismic design, including capacity design provisions, were added in 2003 (Camata 2009). Since newer building codes have more seismic requirements than older codes, RC buildings constructed before the mid-1980s can be expected to be more seismically vulnerable. In Italy, as elsewhere, a large number of these potentially deficient RC buildings exist. Newer construction can also be susceptible to damage, depending on the codes used to design them and the mechanisms for code enforcement and quality control. The situation in Italy is complicated by competing design codes. In 2005, for example, four different design codes (published in different years or by different agencies) were allowed for use in design. In July 2009, as a result of the earthquake, use of the 2008 version—requiring use of the latest provisions and new seismic hazard maps in design—became mandatory (Camata 2009; Dolce 2009).

RESEARCH QUESTIONS AND METHODS

This study uses post-earthquake investigations following the 2009 L'Aquila Earthquake to quantify the seismic vulnerability of Italy's RC buildings, focusing on the impact of deficiencies in seismic design and construction of RC buildings on L'Aquila's commercial, community, and government institutions and residents. Research questions included: What are the characteristics of damaged RC buildings? What is the severity of damage and how much is the building functionality interrupted? What are the sociodemographic characteristics (income level, education, age, gender, etc.) of people occupying RC buildings? What community and government institutions or commercial activities occupy damaged RC buildings? A quick response post-earthquake investigation was needed to gather the necessary data because damage and post-earthquake occupancy data disappears as communities repair and rebuild.

Research methods combined post-earthquake investigations of RC buildings with collection of census and other available data on building occupants and characteristics. Visual inspections were used to document characteristics (location, height, usage, irregularities in plan or elevation, number of units, etc.) of damaged and undamaged RC buildings, to assess the damaged state of the structure and nonstructural components, and to evaluate the loss of building functionality. Loss of functionality is a measure of disruption in structure use, which affects occupant ability to fulfill pre-earthquake economic, familial, and societal responsibilities. Visual inspections of damaged RC buildings were also used to assess the quality of design and construction in the original structure, based on exposed design and detailing characteristics that are normally hidden. However, because design and detailing characteristics could not be observed in buildings that did not sustain structural damage, we were only able to obtain design and construction quality ratings for a limited number of buildings. Damage, loss of functionality, and design/construction quality assessments were assigned systematically, based on a ratings sheet developed before entering the field. Examples of the ratings assigned are shown in Table 1. The study then uses regression analysis and hypothesis testing (t-tests) to explore the relationship between estimated ground shaking, building characteristics, and function on damage state and loss of functionality assessments to identify the characteristics of the most vulnerable buildings.

Additional data about the L'Aquila housing stock and socioeconomic characteristics of building occupants was obtained from the 2001 Italian census. Census building information relates primarily to residential construction and includes building age, construction material, height distribution, building condition, and remodeling and structural upgrades. The census was also used to gather data on age, gender, education and income level of L'Aquila residents. Since this information is aggregated at the city-level, it provides a general description of the affected population.

The study is limited by data that could be gathered during the fieldwork or through subsequent communication with public officials and engineers. With additional support from the National Science Foundation RAPID funding, the impact of damaged RC buildings on the longer-term recovery and rebuilding will be investigated.

BUILDING DATABASE

The database of RC buildings within the city of L'Aquila was assembled through fieldwork conducted from April 22-29, 2009. For each building, catalogued information includes building location (recorded using a GPS device) and street address. Building function is characterized as single family residential (SFR), multi-family residential (MFR), multi-family residential with retail or commercial activity (MFRR), commercial or retail (C/R), industrial (I), or public (P). Other building attributes recorded include the number of stories, number of housing units, observations about irregularities of the structure in plan or elevation, and the type of masonry infill (where apparent). The database buildings are geographically distributed around the L'Aquila historic city center (which was not open to researchers at the time of fieldwork) and are representative of RC construction throughout the city. The inclusion of both damaged and undamaged buildings in the

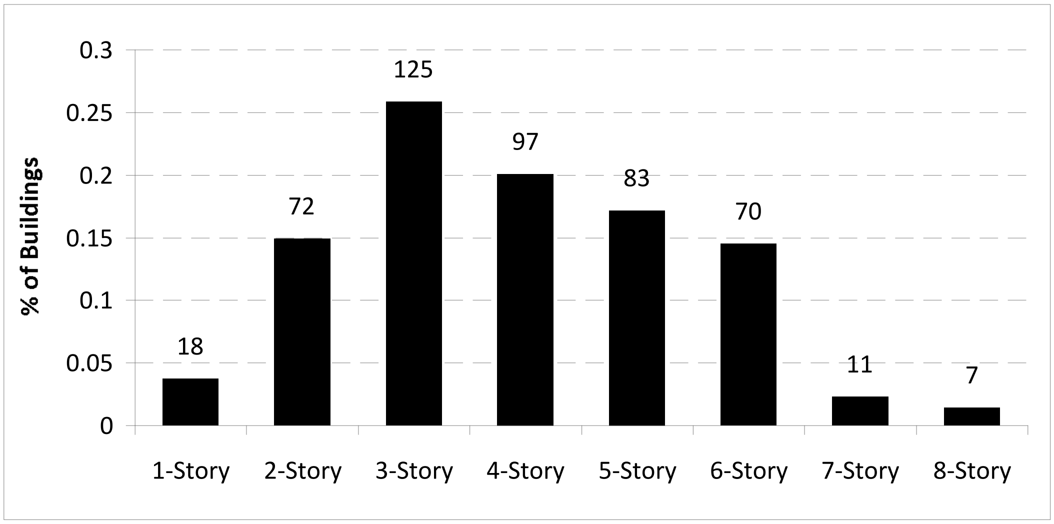
Table 1. Definition of Damage State Classifications for Database Buildings

Damage State	Value	Description
Negligible (N)	1	No damage is visible, either structural or nonstructural. Since the inspection in this study is limited to the exterior, minor damage to contents and interior partitions may be present.
Insignificant (I)	2	Damage requires only cosmetic repair. Repairs needed could include spackling cracks, etc.
Moderate (M)	3	Structural damage has occurred, but is repairable. Existing elements can be repaired in place, without substantial demolition or replacement. For nonstructural elements, this would include minor replacement of damaged partitions, ceilings, or contents.
Heavy (H)	4	Damage is extensive and repair may not be feasible. For nonstructural elements, this would include complete replacement of damaged partitions, equipment, etc.
Collapse (C)	5	Building has completely or partially collapsed.

database is crucial for understanding building and community vulnerability.

A total of 483 buildings (including an estimated 4,618 apartments or residential units) were evaluated. The distribution of database building by height (number of stories) and function are illustrated in Figure 1. Of the 483 buildings, 450 were definitively identified as having RC frame lateral resisting systems; the other 33 are thought to have this structural system. Most buildings had non-structural masonry infill between framing elements, as shown in Figure 2a. Masonry infill typically consisted of two wythes of unreinforced hollow clay tiles (“*mattoni forati*”), though some structures had brick facades, brick or concrete block in one or both wythes or masonry rubble walls. Interior partitions typically consisted of a single wythe of hollow clay tiles. None of the structures examined had visible structural shear walls. Of 483 buildings evaluated, 115 were observed to have torsional irregularities, often due to L-, T-, or C-shape plans. Coincidentally, 115 buildings were also identified as possessing vertical irregularities, such as a soft story or overhang. Roof and floor systems varied, but a one-way system with joists and hollow tiles was common. In the buildings surveyed, column spacing ranged from approximately 12 to 25 feet. Columns were typically square, measuring approximately 18 to 22 inches in each dimension and beam depths were similar. A typical multi-family residential condominium building (shown in Figure 2b) has three to four stories with garages at the ground floor level. This structural system is common throughout Italy (Maffei et al. 2006).

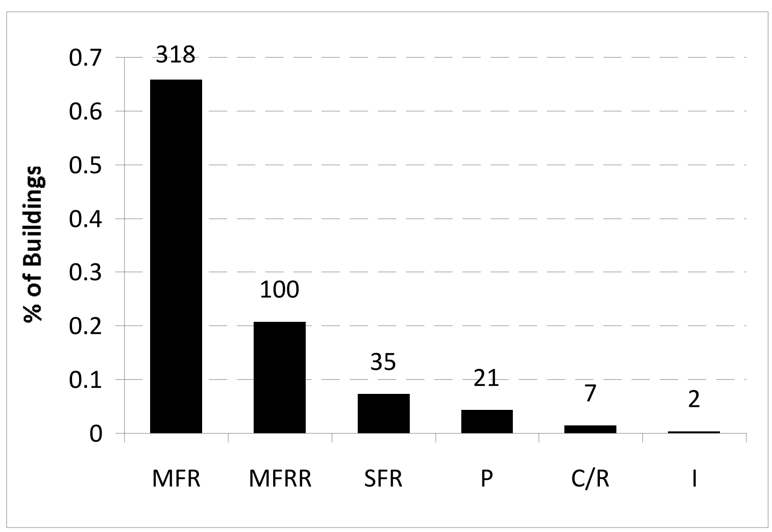
Figure 1a. Distribution of Database L’Aquila Buildings by Building Height (average of 3.9 stories) *Data labels show the number in each group*



The database of RC frame buildings included eight schools and three churches. Other buildings house commercial and retail activity including two pharmacies, numerous medical and dental offices, at least thirteen beauty salons, three major supermarkets (as well as specialty shops for baked goods, fish, and vegetables), six convenience stores, ten bars or cafes, fourteen restaurants, a number of banking, real estate and insurance services, five hardware or carpentry shops, nine mechanics shops, five car dealerships, and numerous other offices, stores, and sports facilities. A post office, police station, funeral parlor, and several day care facilities were also included.

Each structure was classified in one of five damage states, based on an exterior inspection of structural and nonstructural components in the structure. These damage states are defined in Table 1, and illustrated in Figure 3 (next page). In addition,

Figure 1b. Distribution of Database L’Aquila Buildings by Building Function



detailed photographic documentation of damage to structural components and infill walls was collected.

The assessment of post-earthquake functionality records whether (i) residential units were occupied at the time of the inspection, (ii) retail and commercial activities were operational at the time of the inspection, and (iii) repair actions had begun. This assessment results in a rating from *A* to *F*. Grade *A* signifies the structure is operational and has no damage, *B* signifies the structure has some damage but is completely or partially in use, *C* signifies the structure has limited damage, but is not in use, and D signifies there is significant damage and the structure is not in use. A structure with grade *F* structure is destroyed. (Note: Grade *E* is not used, consistent with typical academic grading scales.)

Figure 2a. Structural system and construction practices common in L'Aquila. Photos by Abbie Liel or Kathryn Lynch unless otherwise noted.

Damage assessments for the L'Aquila RC buildings are summarized in Figure 4 on the next page. The majority (68%) of buildings are classified as having negligible or insignificant damage, requiring only cosmetic repairs. Only one of the 483 buildings had collapsed (a collapse rate of 0.2%). The average damage state of 2.2 is slightly above insignificant (DS=2). Figure 4 also illustrates the outcome of the functionality of the assessment. Most of the RC buildings (55%) fell into Grade C, meaning the structures had fairly limited damage (corresponding to negligible or insignificant damage states), but were unoccupied and retail and commercial activity was not open. Fourteen percent of the database buildings were occupied by residents or had open shops at the time of inspection, approximately three weeks after the earthquake. At this time, many of these structures were awaiting inspection by the Protezione Civile Nazionale and reentry was not officially allowed (Bazzurro et al. 2009). However, most were not cordoned off and electricity, water, and other utilities were operational—after minor repairs—within a day of the earthquake in the areas visited (Bazzurro et al. 2009). The activity in database buildings provides a measure of post-quake resilience represented by the loss of functionality assessment. Six buildings were undergoing earthquake-related repairs at the time of inspection. These assessments, shown in Figure 4, are not consistent with an April 18 government statement, which stated that 57 percent of housing was accessible at that time, 19 percent would be accessible in a few days to a month, with the remaining homes being unusable (Corriere della Serra 2009b).

Figure 2b. Typical MFR building included in database (Building 222 shown here).

DAMAGE OBSERVED IN RC BUILDINGS

The most common source of nonstructural damage was cracking or complete brittle failure of masonry infill walls. In some cases (as in Figure 5a), walls experienced X-cracking characteristic of infill shear failure. These cracks often propagated from window openings in narrow wall piers. In other cases, infill failure resulted from out-of-plane failure at the connection between the infill and structural elements, as in Figure 5b. Moderate or more severe damage to masonry infill occurred in 29 percent of database buildings. Minor nonstructural damage included cosmetic cracking in plaster or brick facade or detachment of marble facade from structure.

Failure mechanisms in structural elements included shear failure of short columns (Figure 6a), anchorage failures (Figure 6b), and compressive failure in columns (Figure 6c). These failure modes were initiated by well-known deficiencies in non-ductile RC design, including insufficient anchorage of longitudinal reinforcing bars and use of smooth (rather than deformed) reinforcing bars, column reinforcement lap-splices just above the beam-column joint, and insufficient confinement in plastic-hinge regions of

Figure 3. RC buildings included in database, illustrating a range of damage states.

Figure 3a. Negligible Damage (Building 431)

Figure 3b. Insignificant Damage (Building 206)

Figure 3c. Moderate Damage (Building 485)

Figure 3d. Heavy Structural Damage (Building 214)

Figure 3e. Heavy Nonstructural Damage (Building 325)

Figure 3f. Collapse (Building 372)

Figure 4. Damage state (a) and loss of functionality (b) assessments for database RC buildings.

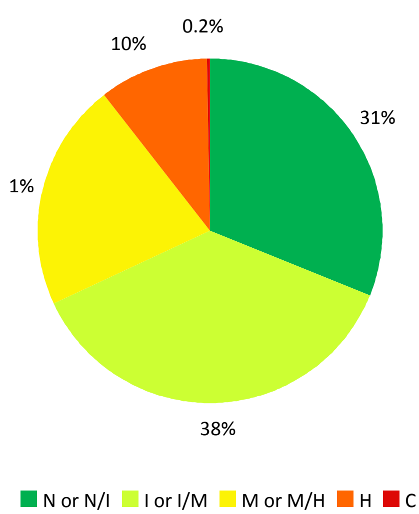


Figure 4a. Damage State

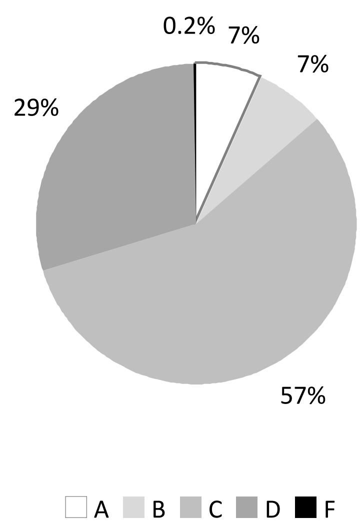


Figure 4b. Loss of Functionality

Figure 5a. Common mechanisms of infill wall failure observed in database RC buildings. Shear cracks are illustrated here.

columns and beams and in the joint region (see also Camata et al. 2009; Bazzurro et al. 2009; Verderame et al. 2009). Short column shear failures most commonly occurred around window openings at the basement or garage level or were caused by infill configurations. Figure 6c illustrates detailing found in many of the structures, including widely spaced transverse reinforcement (approximately 10 inches on center), 90-degree hooks on shear reinforcement, and insufficient development length in beams. This column also shows poorly consolidated concrete and large aggregate size. This building was likely constructed in the 1980s (Camata 2009). Structural damage, however, was relatively limited in the database buildings, affecting only 47 of 483 structures. It is impossible to determine the design and detailing characteristics of the buildings that did not sustain structural damage since these details are not visible, but many are apt to have the design and detailing characteristics described here. In addition to the seismic damage, many structures showed evidence of water damage and corroded reinforcement predating, and likely contributing to, the seismic damage.

Figure 5b. Common mechanisms of infill wall failure observed in database RC buildings. Incipient out-of-plane failure (Building 485) illustrated here.

In buildings with garages or retail at the ground level, most damage occurred at the level immediately above the garage, as shown in Figure 7a-b. In many past earthquakes, for example the 1999 Duzce, Turkey, earthquake (Gur et al. 2009), damage in RC frame buildings is concentrated in soft-stories created by large openings for garages and retail space in the first story. We hypothesize that in many of the database structures, damage concentrates above the garage because the building is located on an incline and the garage/retail level is strengthened by soil on one or more sides. In other cases, like Figure 7c, structural damage is greater at building connections, due to pounding from adjacent buildings and lack of seismic joints.

PREDICTORS OF DAMAGE AND LOSS OF FUNCTIONALITY

Building Characteristics

Database building characteristics, such as height, function, and the presence of plan or elevation irregularities, are correlated with damage and loss of functionality assessments. As illustrated in Figure 8a, the damage assessment tends to increase with building height, such that only 45 percent of buildings with six or more stories assessed were in the lowest two damage states (negligible or insignificant) compared to 90 percent of one- and two-story buildings. Assigning each damage state a numerical value between 1 and 5 (see Table 1), statistical analyses show that the mean damage state is 1.5 (N/I) for buildings with two or fewer stories, 2.3 (between I and I/M) for buildings with three to five stories and 2.8 (I/M to M) for the tallest buildings (six stories or more). These differences in mean damage state are statistically significant at the 5 percent level according to T-tests of the distributions.[3] The increase in damage with building height is consistent with post-earthquake studies of RC frame buildings following the 1999 Chi-Chi, Taiwan (Tu et al. 2009) and Duzce, Turkey (Gur et al. 2009; Hassan and Sozen 1997; Sucuoglu et al. 2007) earthquakes. In L'Aquila, we hypothesize that damage increases in taller buildings because these

[3]T-tests are conducted at a 5% significance level, such that differences between the distributions are statistically significant if p-value < 0.05.

buildings are more flexible and have higher drifts, increasing damage to drift-sensitive nonstructural components like masonry infill walls. Since nonstructural damage dominates the damage assessments in the database, there is insufficient data to know whether structural damage is more likely in taller buildings. It has also been suggested that the alluvial soils in L'Aquila may have influenced ground motion frequency content, contributing to increased damage in taller buildings (Camata 2009). Since taller buildings are more damaged and tend to have more residential units, the 31 percent of buildings in moderate, heavy, or collapse damage states (Figure 4) corresponds to 38 percent of residential units in the database buildings. Figure 8b shows a similar trend between building height and the loss of functionality rating. This relationship is expected, given the correlation between damage state and functionality assessment. Differences in the mean functionality assessment between the height subsets of data are statistically significant according to T-tests with 5 percent significance level.

Damage states and functionality assessments are compared in Figure 9 for different building usage types. The single-family residential (SFR) structures were much more likely to have negligible damage than other types of structures (Figure 9a). In addition, a notable 51 percent of the database SFR were occupied or partially occupied at the time of inspection (Grades A or B), a much higher percentage than other structures (Figure 9b). Of the multi-family residential structures, those with retail (MFRR) had higher damage ratings than those without (MFR) (with mean damage states of 2.5 for MFRR and 2.2 for MFR). The structural and nonstructural systems in these buildings are very similar with retail or garage in the first story.

Figure 6. Structural Failure Mechanisms

Figure 6a (1). Shear failure of short columns (Building 344)

Figure 6a (2). Close up of shear failure of short columns (Building 344)

Figure 6b. Anchorage failure (in this case, in collapsed Building 372)

Figure 6c. Compressive failure at corner columns (Building 325)

Figure 7. Illustration of Damage Concentration Related to Garage Structures

Figure 7a. Damage concentration in the story above the garage in a partially collapsed single-family home in Pianola

Figure 7b. Damage concentration in the story above the garage in an MFR structure in L'Aquila

Figure 7c. Increased damage from pounding between Building 351 and garage structure

However, MFRR buildings tend to be taller, which may account for the increased damage. P-values computed using t-tests show that differences in damage states for different building usage are statistically significant. It is difficult to separate the effect of building height and building usage, since 94 percent of SFR buildings are one or two stories. However, the mean damage state for SFR buildings of 1.16 (N) is lower than the mean damage state for all one or two story buildings (1.5 or N/I), indicating that height does not fully account for these trends.

Structures with strength or stiffness irregularities or discontinuities in the load-path are frequently more susceptible to earthquake-induced damage. In this study, two types of irregularities are considered: (1) plan irregularities in structures that are torsionally asymmetric and (2) elevation irregularities in structures that appear to have soft story, weak story, or other discontinuities, such as a heavy overhang. Structures on a slope (i.e., having a partial level built into the hill) were classified as having irregular elevation. However, structures with first-floor retail or a garage level were not categorized as irregular, since this condition existed in nearly all the structures considered. As Figure 11 shows, buildings having either plan or elevation irregularities are more likely to be in the highest (moderate and above) damage states. A t-test shows that elevation irregularities are a statistically significant predictor of earthquake damage, with p-value = 0.01. The trend with plan irregularities is not statistically significant (p-value = 0.18). Note that this statistical result does not necessarily imply the plan irregularities don't tend to increase damage, but only that the database observations did not show this relationship. Torsional irregularities are frequently observed in heavily damaged buildings, as shown in Figure 10, but can be difficult to identify from exterior visual inspection conducted in this study.

Given the changes in seismic design and construction of reinforced concrete in the past several decades, it might be expected that older buildings would sustain more damage. Unfortunately, it is very difficult to access information on construction year for specific buildings in Italy. In lieu of this data, buildings were visually inspected and classi-

Figure 8. Relationship between building height and (a) damage state and (b) loss of functionality assessment.

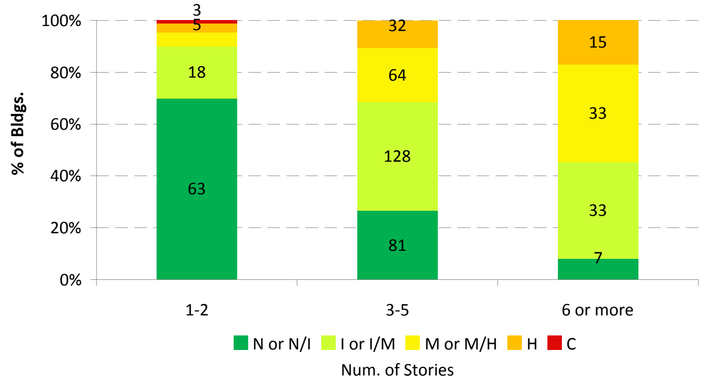


Figure 8a.

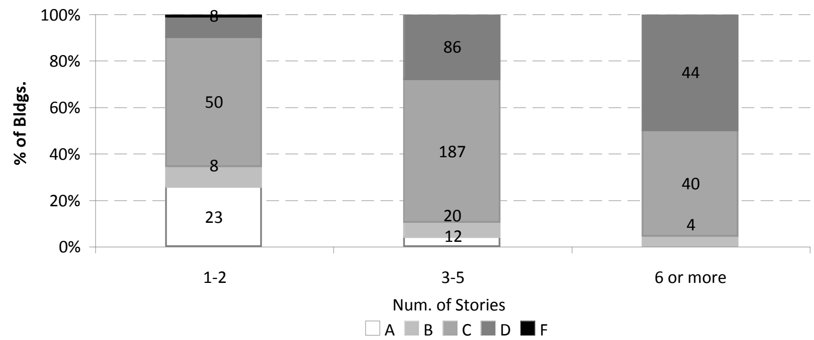


Figure 8b.

Figure 9. Relationship between building usage and (a) damage state and (b) loss of functionality rating.

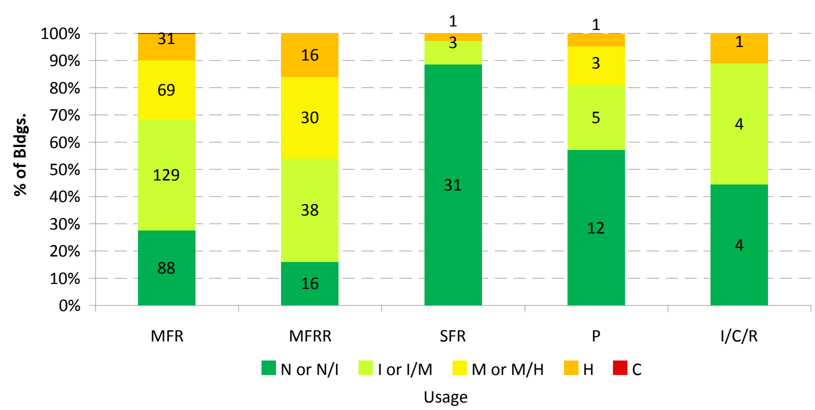


Figure 9a.

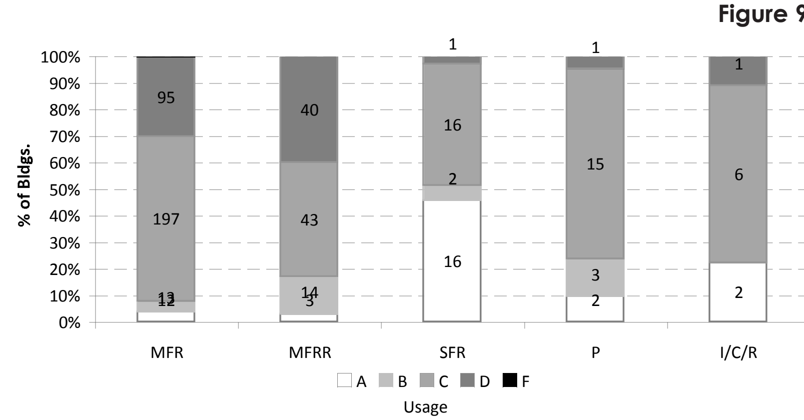


Figure 9b.

Figure 10. A building in Onna had an irregularly configured retaining wall in plan, which contributed to the structural damage (right).
Photos: Guido Camata

fied as (a) relatively new (built in the past 10 years), a category that included 60 buildings or 12 percent of the database, or (b) older. This classification was based on architectural features that differentiate newer construction. The buildings identified as newer had a mean damage state of 1.56 (N/I) compared to 2.28 (I to I/M) for the other buildings, indicating that age/year of construction is a potentially powerful predictor of damage. However, more accurate information is needed to quantify this relationship.

The quality of design and construction of RC buildings can have a significant impact on seismic performance. Important factors affecting building quality include material quality, detailing, and workmanship (Sucuoglu et al. 2007). Evaluation of building quality requires either a detailed inspection of design drawings and the physical building (beyond the scope of this work) or visual inspection of detailing and material quality in damaged buildings. Twenty-five database buildings had severe enough damage to expose design details in structural elements; of these, 24 were characterized as having deficient detailing and workmanship (see examples in Figure 6) and had a mean damage state of 3.8 (H), supporting the observation that severely damaged buildings tend to be of poor quality (Camata et al. 2009). However, this data is limited by our inability to assess the quality of the undamaged and less-damaged buildings and we cannot say, necessarily, whether poorly designed and constructed buildings were more damaged than others.

Ground Motion Intensity and Building Location

Ground-shaking intensity is estimated for each site based on Italy ShakeMap (a program of the Instituto Nazionale di Geofisica e Vulcanologia and the Protezione Civile Nazionale) (Istituto Nazionale di Geofisica e Vulcanologia 2009). ShakeMap predictions for a 1.5 km grid are automatically generated by interpolation between ground motion recordings. Estimates of

Figure 11. Relationship between identified structural irregularities in plan/elevation and damage state.

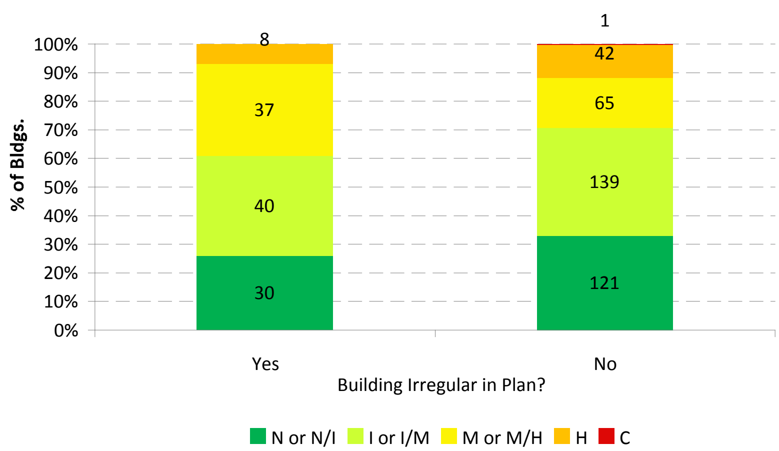


Figure 11a. Structural irregularities in plan.

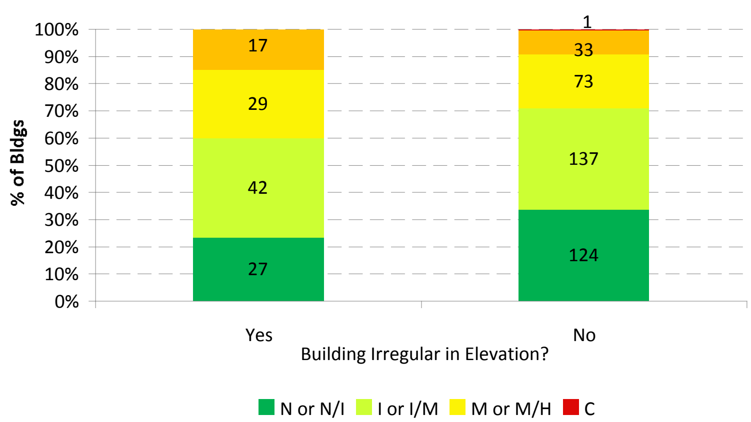


Figure 11b. Structural irregularities in elevation.

Figure 12. Relationship between estimated ground motion intensity (PGA) and damage state and loss

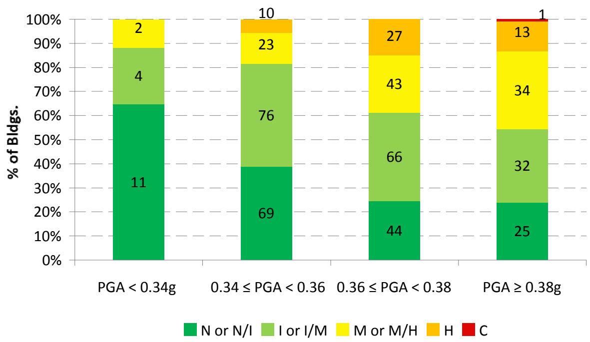


Figure 12a. Damage state.

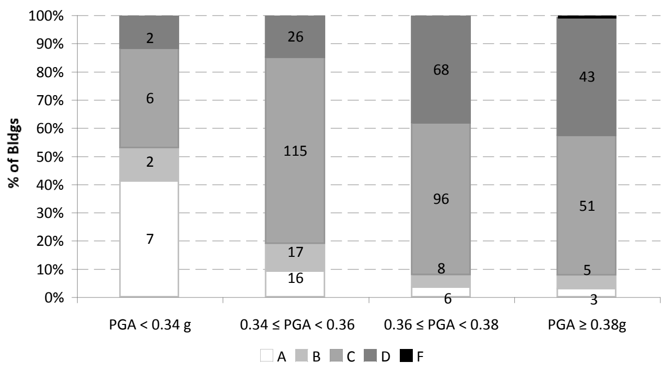


Figure 12b. Loss of functionality.

ground-shaking intensity from the L'Aquila earthquake are based on seismograph recordings the Italian National Seismic Network, including 4 instrument stations in the city (AQA, AQG, AQK, AQV) (Ameri G. et al. 2009). AQG is located on rock, and AQA, AQK and AQV on alluvium (Stewart et al. 2009; Ameri G. et al. 2009). The largest recorded ground motion was 0.66 gravitational acceleration (0.66g) at AQV, and all near-fault instruments recorded at least 0.36g (Ameri G. et al. 2009). In this study, peak ground acceleration (PGA) values are obtained from ShakeMap and further interpolated based on the GPS location of each building, to estimate the PGA at each site. Of course, this approach to estimating ground motion intensity cannot account for site amplification due to soil conditions, which contributed significantly to damage in this earthquake, amplifying ground motions by a factor of four to eight times and altering ground motion frequency characteristics (Camata et al. 2009; Stewart et al. 2009; Camata 2009; Ameri G. et al. 2009). These amplifications vary significantly site to site and across the earthquake-affected area. It also does not capture the large vertical component of ground motion at many sites (Camata 2009; Ameri G. et al. 2009). Nevertheless, the ShakeMap predictions represent the available ground motion estimates at this time in L'Aquila for this purpose.

Based on this approach, the average PGA at the database building sites is estimated at 0.36g. Figure 12 clearly shows higher damage rates in structures subjected to larger estimated PGA. T-tests show that the ground motion bins are statistically significant. The relationship between PGA and building damage is summarized in the fragility curves illustrated in Figure 13, which show the probability of being in or exceeding a given damage state. Fragility functions are assumed lognormal and fitted according to the criteria suggested by Porter et al. (2007). The median values are: insignificant damage—0.33g ($\sigma_{ln} = 0.17$), moderate damage—0.39g ($\sigma_{ln} = 0.12$), heavy damage—0.45g ($\sigma_{ln} = 0.17$), and collapse 3.6g ($\sigma_{ln} = 1.1$). The collapse fragility curve is limited by insufficient data (and is not shown in Figure 12). Given the similarity in construction practices throughout much of Italy these fragility curves are expected to be applicable to RC frames buildings in many cities.

The spatial distribution of damage in database buildings is illustrated in Figure 14. There are concentrations of moderate and severely damaged buildings in the area north of Via Raffaele Paolucci, marked A on the map, and between Viale Corrado IV and Viale 25 Aprile (area B). Areas A and B correspond loosely to locations with the highest esti-

Figure 13. Fragility functions predicting the probability of exceeding a specified damage state as a function of ground motion intensity for L'Aquila RC buildings.

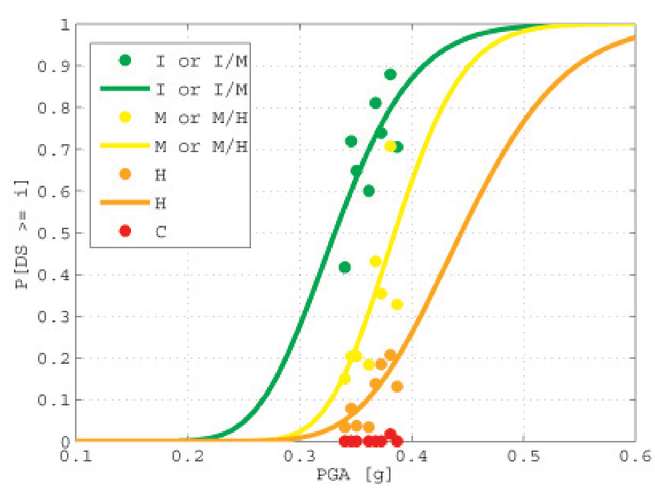


Figure 14. Damage patterns observed in database buildings in the newer areas surrounding the historic city core (shown in the center of the map). The city core was closed at the time of fieldwork.

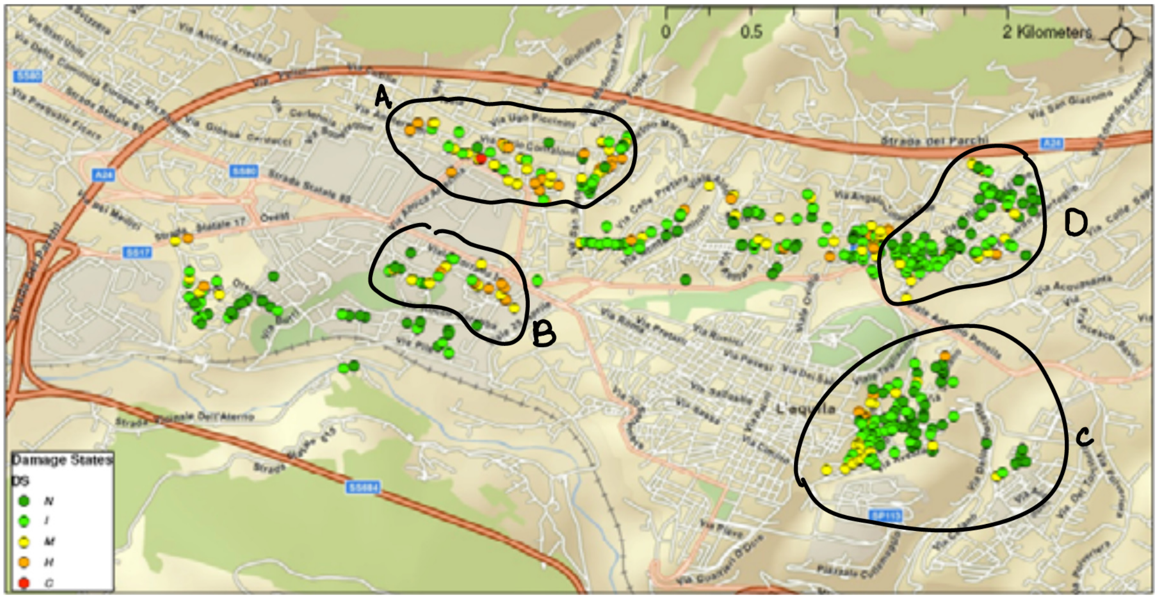


Figure 15. PGA estimates at database sites.

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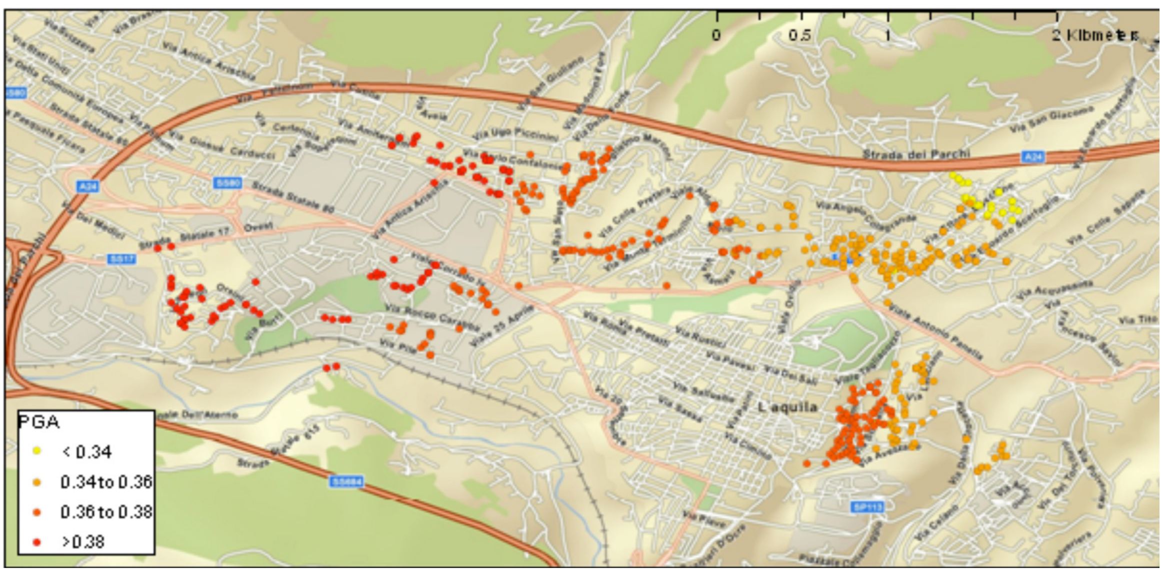


ground shaking, as shown in Figure 15. Inspected areas to the east (around Via Strinella and north-east of Via Antonio Panella, areas C and D) experienced relatively less damage. These areas were also more likely to have occupied residential buildings or open retail.

SIGNIFICANCE FOR L'AQUILA HOUSING STOCK

Detailed database information gathered in the study can also be used to investigate the overall societal impact of vulnerabilities in RC buildings. The database buildings are representative more generally of RC housing stock in L'Aquila. Key characteristics of L'Aquila residential buildings are described in the 2001 Census (Istituto nazionale di statistica 2001), the most recent year for which data

[4]These 453 residential buildings include all database buildings categorized as SFR, MFR and MFRR.

is available, which estimates that the municipality of L'Aquila has 14,088 residential buildings. The 453 database residential buildings[4] therefore relate information about approximately 3.2 percent of L'Aquila's housing stock (buildings), and include roughly 14 percent of the city's 32,676 residential units (apartments). By appropriately extending database findings to the broader L'Aquila stock of residential buildings, the extent of damage associated with deficient RC construction can be estimated.

In the municipality of L'Aquila, the bulk of the residential construction is bearing masonry and 29 percent (or 4,113 buildings) are constructed of reinforced concrete, as shown in Figure 16a. The actual number of RC buildings in L'Aquila in 2009 likely exceeds the 4,113 counted in 2001, given population growth of more than 5 percent since 2001 (Istituto nazionale di statistica 2008). Compared to the rest of the province of L'Aquila, which is more rural, the city has a slightly higher prevalence of reinforced concrete (29 percent of buildings, compared to 22 percent for the province). The distribution of residential buildings in the city of L'Aquila, according to year of construction, is shown in Figure 16b. RC buildings tend to be newer; of these, approximately 89 percent[5] have been constructed since 1962. Fifty-five percent were constructed before 1982. This data implies that approximately 265 of the database buildings were built before 1982, making them unlikely to have ductile design and detailing features of modern seismic design.

The distribution of building height among L'Aquila residential buildings is illustrated in Figure 16c. The majority of structures have one or two stories. Bearing masonry construction accounts for 8,614 buildings are bearing masonry in L'Aquila (Istituto nazionale di statistica 2001), and we assume that 90 percent of these buildings are one to two stories. Therefore, a realistic distribution of building heights for other residential buildings (of which the vast majority are reinforced concrete) includes approximately 35 percent one- to two-story structures, 41 percent three-story structures, and 24 percent structures with four or more stories. The database RC buildings tend to be taller, with 19 percent having one to two stories, 26 percent having three stories, and 54 percent with four or more stories (Figure 1).

Figure 16. Residential buildings in the City of L'Aquila, by type of structural system, year of construction, and building height (Istituto nazionale di statistica 2001).

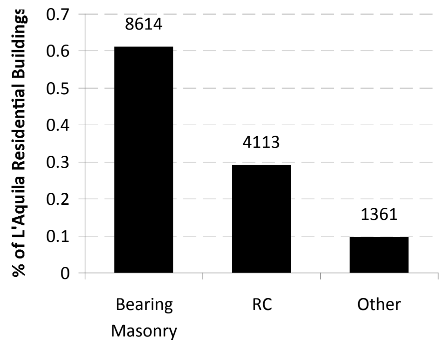


Figure 16a. Structural system.

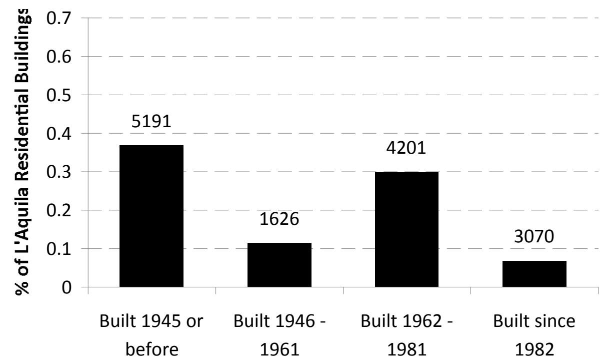


Figure 16b. Year of construction.

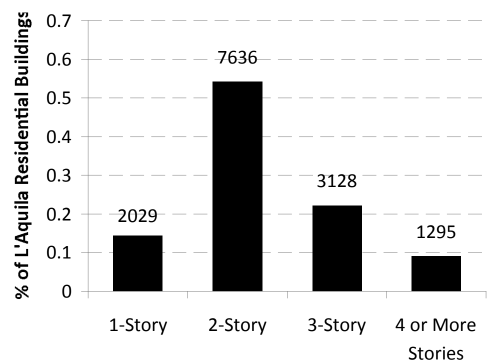


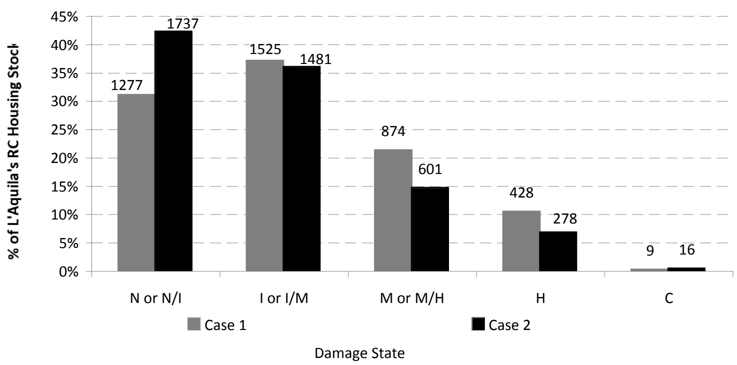
Figure 16c. Building height.

Most homes in L'Aquila are privately owned (92%). Of those that are occupied, 75 percent are owner-occupied, but approximately 36 percent were vacant at the time of the Census (Istituto nazionale di statistica 2001). The Census also reports maintenance, restoration, and renovation of residential buildings, showing that approximately 7 percent

[5]The data reporting year of construction for RC buildings in the 2001 Census is aggregated for L'Aquila province. However, the RC buildings in L'Aquila contribute significantly to the province total, and there is little reason to suspect that this data would vary across the province.

of residential buildings in L'Aquila province have had structural upgrades (including seismic retrofit activity) in the preceding 10 years (Istituto nazionale di statistica 2001). There is not a significant difference in rate of structural intervention according to building ownership, but those properties that are renter-occupied are less likely to have been remodeled or upgraded. On the basis of this data, it seems unlikely that many of the database structures have undergone significant retrofits. Most RC residential buildings are assessed in the Census as having either an excellent (45%) or good (50%) physical condition (Istituto nazionale di statistica 2001), but this evaluation does not directly consider seismic resistance.

Figure 17. Estimated damage state for all RC residential buildings in L'Aquila. Cases reflect different assumptions about distribution of buildings by height.



Through extrapolation to the rest of the L'Aquila housing stock, the 483 database buildings can be used to estimate earthquake damage and impacts for all RC buildings in L'Aquila. Predictions of the number of buildings in each damage state in the city of L'Aquila following the April 2009 earthquake are presented in Figure 17. The two sets of estimates are based on different underlying assumptions. In Case 1, it is assumed that the height distribution of the L'Aquila RC buildings is the same as the height distribution in the original database (illustrated in Figure 1). In Case 2, the height distribution is updated based on available Census data for L'Aquila (Figure 16), assuming (as above) that the bearing masonry buildings are mostly one or two stories. It is important to account for the height distribution, given the relationship found between earthquake damage and height (Figure 8). In both cases, we assume that L'Aquila has 4,113 RC residential buildings based on 2001 data (Istituto nazionale di statistica 2001) and that buildings not included in the database were subjected to similar levels of ground shaking as those in the database. Since the database buildings are geographically distributed, this approach is a reasonable first approximation. We also assume that the irregularities observed in the database construction are representative of other RC buildings in L'Aquila.

Case 2 predicts that 1,737 or 42 percent of RC residential buildings in L'Aquila experienced negligible damage and 879 (21.3%) of buildings are predicted to be in moderate or heavy damage states. More buildings are in moderate or heavy damage states in Case 1, because of the higher assumed percentage of taller buildings. Estimates for the collapse-limit state vary between nine (Case 1) and 16 buildings (Case 2). The actual number of collapsed RC buildings in L'Aquila is unknown, but includes, at the least, the one database building (Building 372), a university dormitory (Rossetto et al. 2009; Verderame et al. 2009), the Hotel Duca d'Abruzzi (Rossetto et al. 2009; Verderame et al. 2009), two soft-story structures in the Pettino area (Camata et al. 2009; Rossetto et al. 2009; Verderame et al. 2009), a residential building in Porta Napoli (Verderame et al. 2009), a five-story residential structure on Via XX Settembre (Rossetto et al. 2009), and at least one other (Camata et al. 2009); a total of 8 buildings. The EERI team visited 15 concrete buildings with "dramatic failures" (Bazzurro et al. 2009). The database estimates, therefore, show good agreement with the limited information available.

Fieldwork data for RC buildings collected in this study suggest that between 601 and 874 residential buildings are estimated to be moderately damaged and 278 to 428 buildings are estimated to be heavily damaged. These damage states require significant repairs (moderate) and building replacement in some cases (particularly in the cases of heavily damaged buildings). Since these buildings include 22-32 percent of RC buildings in L'Aquila and six to nine percent of the total number of residential buildings, these vulnerabilities could have a significant effect on the city's recovery; severely disrupting lives and commercial activities in these building. The impact on local businesses is likely to be critical because of the prevalence of retail and commercial activity, especially in the taller, more damaged buildings. These types of structures house a variety of services, including shops, doctors' offices, and government agencies.

OCCUPANTS OF RC BUILDINGS IN L'AQUILA

Demographic and socioeconomic characteristics of the residents and users of affected RC buildings in L'Aquila are explored here because they could represent indicators or causes of social vulnerability (National Research Council 2006; Cutter 1996). Demographic and socioeconomic data is publicly available at the municipal and provincial level (Istituto nazionale di statistica 2001). Since the spatial resolution of the data is not fine enough to quantitatively explore relationships between socioeconomic characteristics and building damage, a qualitative approach is taken here to describe who occupies vulnerable RC construction.

Figure 18. Population Statics for L'Aquila, Italy

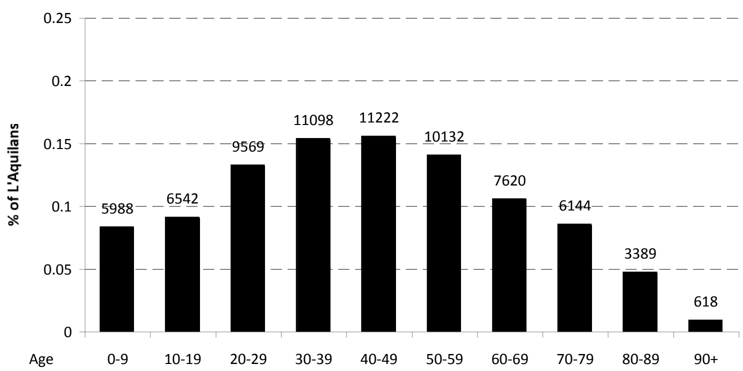


Figure 18a. L'Aquila population by age (Insituto nazionale di statistica 2008).

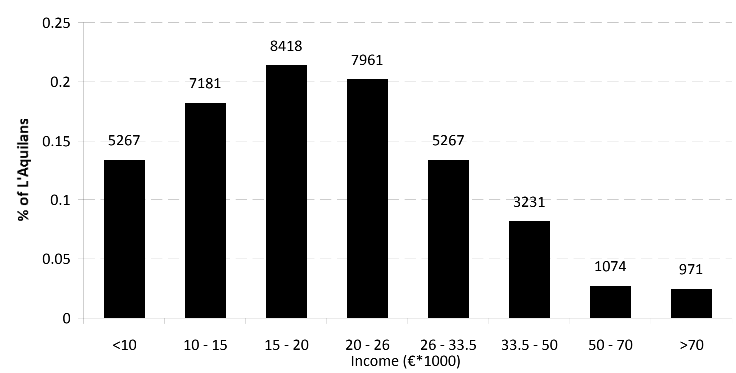


Figure 18b. L'Aquila population by taxable income (Comuni-Italiani 2005).

The City of L'Aquila had a population of 72,550 as of January 2008 (Istituto nazionale di statistica 2008). The population has grown 5.9 percent from 2001 to 2008, a notable increase, given the population declines in much of Italy. L'Aquila has a slightly higher percentage of female (52%) compared to male residents. The age distribution of residents is shown in Figure 18. Compared to Italy as a whole, L'Aquila has fewer young people (ages 0 -24) and more elderly (older than 65), but the differences are small. In addition, the residents of L'Aquila tend to be fairly well educated; 14 percent of residents in the six and older category have a university degree and 35 percent have a secondary school diploma, compared to 7.5 percent and 26 percent nationally (Istituto nazionale di statistica 2001). Similar to the rest of Italy, 38 percent of the population is employed (Istituto nazionale di statistica 2001). However, the distribution of employment among different sectors in the economy differs in L'Aquila from elsewhere in Italy. In L'Aquila, a higher percentage of the work force is employed in health, education, social services, and in public administration and defense, fewer work in agriculture, manufacturing, and tourism. L'Aquila is home to several military installations. L'Aquila residents reported a median income of €21,312 (US$31,169) on their 2005 taxes, distributed as shown in Figure 18b (Comuni-Italiani 2005). This income is higher than the average for the region of Abruzzo (€17,802, or US$26,034) and comparable to the national average of €22,535 (US$32,959).

The database of RC buildings developed in this study includes an estimated 4,618 residential units, and since each houses 2.5 people on average (Istituto nazionale di statistica 2001), it is estimated that the homes of approximately 11,545 people, or 16 percent of L'Aquila's population was evaluated. Of these, 21 percent[6] lived in homes with negligible (N or N/I) damage, 40 percent lived in homes with insignificant damage, 26 percent lived in homes with moderate damage, and 12 percent (approximately 1,385 people) experienced heavy damage to their homes. Other people were also impacted because their workplaces are located in heavily damaged buildings. Looking at the data for functionality assessments, 11 percent of residential units were in buildings that were occupied or partially occupied at the time of the fieldwork (Grades A and B). Fifty-four percent were in buildings with loss of functionality (Grade C), indicating the building had limited damage, but was not in use. These

[6]The percentages in this paragraph are slightly different than those shown in Figure 4, because they are based on the damage states and functionality assessment distributions by number of apartments, rather than by number of buildings.

buildings could potentially be occupied in a timely manner. An estimated 35 percent of inspected units were in buildings with loss of functionality (Grade D or F), providing an estimate of the number of people permanently displaced or needing rebuilding assistance. In late April, the Protezione Civile Nazionale estimated 34,000 displaced people (Rossetto et al. 2009) or approximately 45 percent of L'Aquila's population. This estimate seems low, given the 11 percent rate of occupancy or partial occupancy observed during our fieldwork at the same time.

RC frame buildings have been the predominant form of construction in urban and suburban areas of L'Aquila over the last 30 to 40 years. We were unable to obtain information to know specifically the income, age, education level, or gender of the people residing in the most damaged buildings or those permanently displaced by the 2009 L'Aquila earthquake. However, the database suggests that people residing in high-rise condominium buildings are the most vulnerable. To the extent that these residences are mostly owner-occupied, but not particularly extravagant, it seems likely that these residents are neither the poorest, nor the wealthiest, in L'Aquila's population. Only a small number of the database buildings (e.g., buildings 142 – 144) were in notably poor condition, perhaps indicating residents with lower income. To the extent that wealthier families are able to live in low-rise, single-family residential construction—which suffered much less damage—they would be less likely to be affected.[7] In many ways, the occupants of these buildings likely represent a broad spectrum of L'Aquila's population. Studies of other disasters have suggested that low-income households tend to be more vulnerable, in part because they occupy structures that are older, lower-quality construction or are less-well maintained (National Research Council 2006). While there is insufficient data to refute or confirm this statement in L'Aquila, this study suggests that, although many physical and social factors contribute to choices about living in vulnerable RC structures, they are certainly not limited to income and other sociodemographic characteristics. Additional research, such as a telephone survey would potentially be useful to obtain more information about the household characteristics of those most significantly impacted by damage to RC buildings.

CONCLUSIONS

This study investigates the vulnerability of RC frame buildings in the 2009 L'Aquila, Italy, earthquake and the impacts of this damage and building closure on the L'Aquila population. Results are based on post-earthquake fieldwork to develop a database of building characteristics, assessed damage state and loss of functionality ratings for more than 400 buildings in L'Aquila. While findings are specific to RC construction in L'Aquila (and more generally, Italy as a whole), the study provides insights into the potential impact of deficiencies in RC buildings on the resiliency of a community, even when structural damage is fairly limited. Although problems with nonductile RC construction are well-known, an examination of the potential consequence of these problems and their impact on building occupants and functionality are critical to developing better plans for retrofit or rebuilding.

Sixty-eight percent of buildings were classified as having negligible or insignificant damage visible from the exterior. The findings of this study show that seismic damage increases with building height, such that structures with one and two stories generally experienced negligible damage while the tallest buildings (defined as those with six or more stories) generally experienced insignificant or moderate damage. Multifamily residential construction incurred significantly more damage than single-family residential construction. Residents and businesses in older mid-rise condominium structures were therefore the most vulnerable in RC frame buildings. In addition, the analyses showed that buildings with strength and stiffness irregularities, particularly in the height (elevation) of the structures, were more damaged. Despite the crude nature of the ground shaking estimates used at each site (neglecting soil conditions and site amplification affects), the study found a relationship between the estimated ground shaking intensity at each site and building damage. Although data on building age was extremely limited, the study also seemed to indicate that newer structures on the whole performed better, likely because of improvements in building code and construction practices in the past few decades. Similar trends were observed for loss of functionality assessments.

The 32 percent of RC buildings that experienced moderate or heavy damage or collapse and the 86

[7] It may also be true that wealthier people prefer to live in older, historic structures. Although not directly considered in this paper, these structures suffered significant damages and collapse in the L'Aquila earthquake.

percent of buildings not used in the weeks and months following the earthquake have a significant impact on the lives and livelihood of L'Aquila residents. Severely damaged buildings (most of which experienced predominantly nonstructural damage) will be closed or unoccupied for some time to allow for repair or rebuilding. Buildings without significant damage were also been closed as inspections were slowly carried out and people fearful of an aftershock delayed returning to their home. Retail and commercial activities commonly found in RC buildings were hampered by building damage, which displaced employees and customers.

Engineering solutions to reduce vulnerability of RC buildings to structural and nonstructural damage are well-established. Given the significant contribution of damaged infill walls to damage and disruption—and even deaths (Bazzurro et al. 2009)—current design and construction procedures for these infill walls are questionable and an integrated approach to design of nonstructural and structural components is needed. Of particular relevance here are methods for strengthening infill walls or tying them to the framing system. In the L'Aquila earthquake, the very small number of infill walls with reinforcement was observed to have markedly better performance (Camata et al. 2009). The existing code provision that requires engineers to check the stability of infill walls is rarely (if ever) considered in the design process (Camata 2009). RC frames with structural shear walls typically experience less damage because drifts are limited (e.g. Gur et al. 2009). These walls can be added as a retrofit measure. The costs of improving structural design and infill wall connections is relatively small in new construction, but is much more significant in retrofit or repair of existing construction. These costs must be compared, however, to the costs of neglected design in infill walls or poorly detailed reinforcement, as in L'Aquila. This study also provides information as to which buildings are the most vulnerable, suggesting that simple tests such as looking at building height, checking for irregularities, estimating ground-shaking and, examining building age, could potentially be used to identify the highest risk RC structures in L'Aquila or Italy. Design and detailing information, while useful, is difficult to obtain. These screening procedures do not require complex analyses or inspection to prioritize vulnerabilities. Knowledge of who is vulnerable in RC frames suggests, because residents of multifamily condominium structures are the most vulnerable, that people will need to group together to ensure that repairs, retrofits, and new buildings improve safety and reduce damage.

The impact of the L'Aquila earthquake on local residents, community groups, institutions, and buildings is ongoing. Many activities that constitute critical components of recovery, including "the provision of resources to assist households and business with reconstruction" and "the development and implementation of reconstruction plans" were in their early stages at the time of this report (National Research Council 2006). Immediately following the earthquake, all residents were evacuated until buildings could be inspected, and the government initially promised on April 18 that 75 percent of homes would be usable within 30 days (Corriere della Serra 2009b). Although the Protezione Civile Nazionale earned initial praise in its response to the L'Aquila earthquake and the establishment of temporary housing (Rossetto et al. 2009), the building inspection process and procedures for allowing people to return home has been slow and disorganized (Camata 2009). As of May 2, an estimated 24,000 buildings had been evaluated by over 1,500 inspectors, 65 percent of them green-tagged—indicating the inspection found no apparent structural damage and the structure can be occupied (Bazzurro et al. 2009)—but by mid-July, most residents had not been allowed to return (Camata 2009). Unlike past Italian earthquakes, the recovery and reconstruction process in L'Aquila was administrated directly by the central government. The government issued the first bid for reconstruction work on May 5, 2009, in a project called Complessi Antisismici Sostenibili Ecosostenibili (in English, seismic resistant, sustainable, and eco-sustainable) or C.A.S.E. The project consists of the construction of 150 seismically isolated buildings for approximately 4,500 apartments at the cost of €330 million. The buildings must be completed by December 2009 (Protezione Civile Nazionale 2009). In June, two ordinances (3778 and 3779) were issued that subsequently mandated inspections to estimate the costs of repair and reconstruction for homes with that only had non-structural damage (leaving those with significant structural damage to be considered separately). At the time of this report, however, little had been done because of lack of clarity in the provision language and confusion as to how the technical and construction expenses would be funded, specifically the expected contribution from citizens (Camata 2009). Input from the local community and politicians in the recovery and reconstruction process had been extremely limited. Recovery was further complicated by the Italian government's decision to hold the G8 summit in L'Aquila in July 2009, as well as criminal investigations into the collapse of buildings (Camata 2009; Corriere della Serra 2009c; Corriere della Serra 2009a). The government goal is to have victims in permanent housing by winter 2009 (Camata 2009; Corriere della Serra 2009d), but this looks increasingly unlikely given the slow progress thus far.

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