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2016-17 Central Italy Earthquake Sequence: Seismic Retrofit Policy and Effectiveness

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ABSTRACT

The 2016-17 Central Italy Earthquake Sequence consisted of several moderately-high magnitude earthquakes, between Moment Magnitude **M**5.5 and **M**6.5, each centered in a different location and with its own sequences of aftershocks, spanning several months. To study the effects of this earthquake sequence on the built environment and the impact on the communities, a collaborative reconnaissance effort was organized by the Earthquake Engineering Research Institute (EERI), Eucentre Foundation, European Centre for Training and Research in Earthquake Engineering (EUCentre), and the Rete dei Laboratori Universitari di Ingegneria Sismica (ReLuis). The effort consisted of two reconnaissance missions: one following the Amatrice Earthquake of August 24th 2016, and one after the end of the earthquake sequence, in May 2017. One objective of the reconnaissance effort was to evaluate existing strengthening methodologies and assess their effectiveness in mitigating the damaging effects of ground shaking. Parallel studies by the Geotechnical Extreme Events Reconnaissance (GEER) Association, presented in a companion paper, have demonstrated that variations in ground motions due to topographic site effects had a significant impact on damage distribution in the affected area. This paper will present that, in addition to these ground-motion variations, the variation in vulnerability of residential and critical facilities was observed to have a significant impact on the level of damage observed in the region. The

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damage to the historical centers of Amatrice and Norcia will be used in this evaluation: the historical center of Amatrice was devastated by the sequence of earthquakes, while the significant damage in Norcia was localized to individual buildings. Amatrice has not experienced the same number of devastating earthquakes as Norcia in the last 150 years. As a result, its building stock is much older than that of Norcia and there appeared to be little visual evidence of strengthening of the buildings. The distribution of damage observed throughout the region was found to be indicative of the effectiveness of strengthening and of the need for a comprehensive implementation of retrofit policies.

INTRODUCTION

The 2016-17 Central Italy Earthquake Sequence began with the Amatrice Earthquake of August 24th 2016, which had a Moment Magnitude (M) of M6.1 and caused significant damage and life loss in the town of Amatrice and nearby villages. The event with the largest magnitude, M6.5, however, occurred on October 30th 2016 centered near the town of Norcia, North of Amatrice, with a larger affected area which overlapped that of the Amatrice Earthquake. This earthquake, however, had no fatalities because most of the affected areas had been evacuated after two significant events on October 26th 2106, centered near Visso, North-East of Norcia, both with Moment Magnitude greater than M5 (M5.9, M5.4). The last significant event in the sequence occurred on January 18th 2017, had a Moment Magnitude M5.5, and was centered South of Amatrice. The seismological characteristics of these events and data on the ground-motion recordings have been presented in the literature (GEER 2016, 2017, ReLuis-INGV 2016, Zimmaro et al. 2018, Luzi et al. 2017).

The findings presented in this paper are based on collaborative reconnaissance effort organized by the Earthquake Engineering Research Institute (EERI), Eucentre Foundation, European Centre for Training and Research in Earthquake Engineering (EUCentre), and the Rete dei Laboratori Universitari di Ingegneria Sismica (ReLuis), with on-site support from the Italian Department of Civil Protection (Dipartimento della Protezione Civile, DPC), the government’s emergency-management agency. Additional collaboration was provided by the Geotechnical Extreme Events Reconnaissance (GEER) Association during the organization and planning phase. The effort consisted of two reconnaissance missions: one during the week of September 12th 2016, following the Amatrice Earthquake, and one during the week of May 8th 2017, after the end of the earthquake sequence once it was safe to enter the restricted areas. The following towns were visited during the first reconnaissance mission:

Accumoli, Illica, Amatrice, Saletta and other neighboring fraction of Amatrice, Amandola, Castelluccio di Norcia, Norcia (briefly), Arquata del Tronto, and Pescara del Tronto, with stops along the way. The following towns were visited during the May reconnaissance mission: Visso, Ussita, Castelsantangelo Sul Nera, Camerino, Campi, Norcia, Cascia, Illica, Accumoli, and L'Aquila. Two days were spent in Norcia and its neighboring areas. Amatrice was not yet accessible during the second reconnaissance mission. The first reconnaissance mission in September only performed a quick survey of the historical center of Norcia because it did not appear have been affected by the Amatrice Earthquake. Epicentral distances for some of these localities, and for those closest to the epicenters (in *italic*), are given in Table 1 (INGV-CNT, 2018). The table provides distance from the Municipio (City Hall) to the epicenter, as reported by INGV-CNT, as well as an approximate range of population at those localities. Epicentral distances were provided by INGV-CNT only for localities within 20km. The location of the municipalities visited during the reconnaissance missions is shown in Figure 1. Figure 1A and Figure 1B show the USGS ShakeMap and surface projection of the Amatrice Earthquake (August 26th) and the Norcia Earthquake (October 30th), respectively. The figures also shows the municipalities visited during the two reconnaissance trips, September 2016 and May 2017, respectively. All four epicenters are shown in both figures (USGS, 2017).

The reconnaissance teams, composed of structural and lifelines engineers, focused on structural systems, both buildings and bridges. In addition to focusing on the engineering aspects of individual structures for performance/damage assessment, the teams' main objectives were to gather observations on the types of structural-strengthening systems implemented and their effectiveness in reducing damage, the operations procedures for emergency management protocols, the performance of critical structures such as schools and hospitals, and observing the impact of the earthquake on the social fabric of the communities for recovery. The focus of this paper is limited to the type and effectiveness of strengthening measures from both an engineering and a policy aspect, with a note on critical structures such as schools and hospitals. The observed difference in performance and damage distribution in the towns of Amatrice and Norcia will be used an example.

There are two primary types of construction in the area affected by the earthquake sequence: older unreinforced stone or brick masonry construction, found primarily in the historical centers of towns, and more modern reinforced-concrete structures, distributed in the periphery of the towns. Even though fewer reinforced-concrete structures experienced significant damage, they affected a larger portion of the population because of the larger number of residents in one building, hence demonstrating that their vulnerability needs to be considered as well.

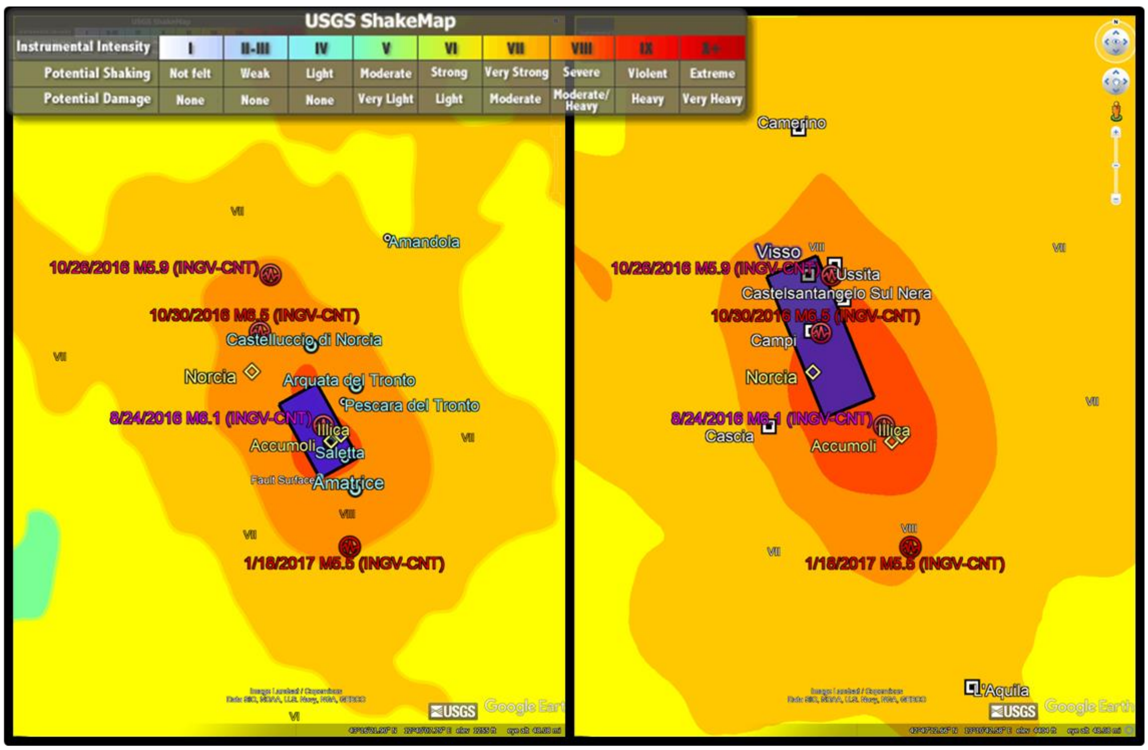
The objective of this paper is to present findings based on visual observations during the reconnaissance effort. It is difficult to determine the presence and/or type of strengthening method, as well as the actual damage level, through visual inspections from the street. Further studies are recommended where strengthening and damage statistics are collected for each municipality of interest. The data collected would quantify the numbers, and percentages, of different building types and strengthening methodologies. These data would then be compared to damage data collected from systematic evaluation of each building where inspectors can access the buildings. Drawing quantitative conclusions from the team's reconnaissance observations would bias the data toward higher damage states because it is difficult to assess buildings that look undamaged from the outside, both in terms of damage and of strengthening method and such data was, therefore, not collected.

A companion paper in this series by A. Sextos and his GEER-ReLuis collaborators focuses on the topographic site effect and incremental building damage during the 2016 Central Italy Earthquake Sequence where such data was collected more systematically (Sextos et al., 2018). Sextos and his co-authors present the correlation between building damage and site effects. In presenting the incremental-damage data, they note that masonry structures become highly vulnerable in subsequent earthquakes because of their brittle nature, even though they may have experienced minor damage initially. These findings are consistent with the findings presented in this paper, and further studies are recommended to combine the data both in terms of site effects and building and strengthening type. It is worth investigating whether passive strengthening methods such as the steel ties presented in this paper are effective in preserving the integrity of the structure, thus improving their ductility capacity when subjected to repeated seismic events.

Table 1. Epicentral Distance and Population of Selected Localities (INGV-CNT, 2018)

Locality	Population	Distance to Epicenter (km)			
		August 24 M6.1	**October 26 M5.9**	**October 30 M6.5**	**January 18 M5.5**
Amatrice	2500-3500	9	*	*	11
Norcia	5000-1000	16	13	5	*
Accumoli	700	1	*	19	19
Arquata del Tronto	1200-4500	10	*	17	*
Castelsantangelo sul Nera	300	*	3	8	*
Visso	1100-1400	*	4	11	*
Ussita	400-2000	*	4	13	*
Preci	*700-2500*	*	*8*	*8*	*
Capitignano	*700*	*	*	*	*2*
Montereale	*2600-3200*	*	*	*	*3*

*: Epicentral Distance exceeds 20km and is not reported by INGV-CNT



A. September 2016 Reconnaissance
August 24th Amatrice Earthquake

B. May 2017 Reconnaissance
October 30th Norcia Earthquake

Figure 1. Municipalities visited during Reconnaissance overlaid with Shakemaps and fault-surface projection of relevant earthquakes (USGS, 2017). Epicenter locations of critical events (INGV-CTN, 2018)

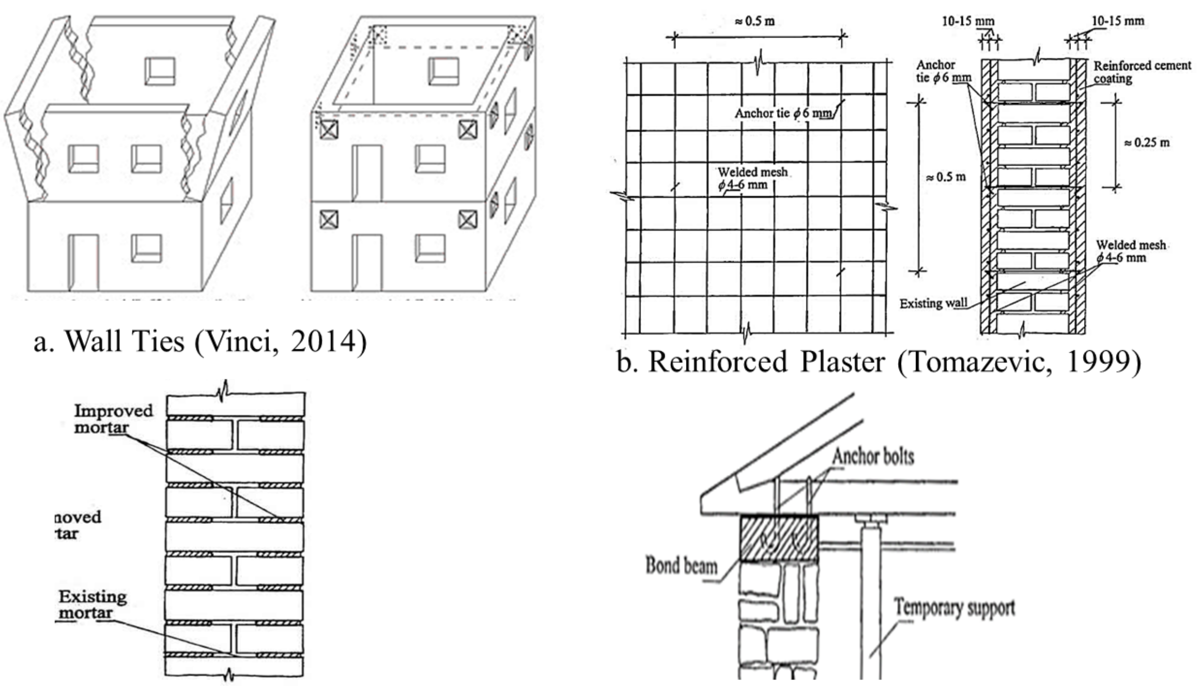
HISTORY OF EARTHQUAKE POLICIES IN ITALY

The vulnerability of a building can be attributed to the type, age, and quality of construction, as well as the type, age, and level of strengthening applied to the existing structure. Because the country of Italy was not unified until the end of the 19th century, earthquake-resistant design practices did not spread across the region easily. Professor Bellicoso, in the Department of Architecture and Urbanism at the University of L'Aquila Italy has written a detailed history of seismic-resistant legislation in Italy (Bellicoso, 2011). Many resources listing relevant earthquakes in different regions in Italy, such as list of key earthquakes in the Umbria-Marche Region by V. Castelli (Castelli, 2017), provide details on the evolution of seismic design and strengthening practices in Italy. A summary of relevant points is given in this section.

The earliest building standards in the Italy were published within the Kingdom of Napoli following devastating earthquakes in 1627 and 1784 in what are now the Campania and Calabria regions. These early standards gave general regulations on requiring a framing system and strong foundations. After the earthquake of 1859, which destroyed half of the town of Norcia, the governing Papal States imposed the region's first construction standards, imposing geometric constraints and requiring certain building techniques: 1. A building-height limit of 8.5m (28ft); 2. A minimum wall thickness of 60cm (2 feet) (outer and inner walls); 3. The external walls had to have tapered buttresses with a 1:20 thickness:height ratio at the base; 4. The interior and exterior walls had to be connected to form a single mass; 5. The use of vaults only at the ground floor; and 6. The openings for doors and windows had to be as far as possible from the exterior walls or wall ends and had to be aligned vertically. These design requirements are observable in many buildings in Norcia which have withstood the seismic sequence of 2016-17 with damage ranging from none to moderate.

More advanced design standards and seismic zonation maps were developed in the second half of the 20th century, with the most rigorous standards released in the late 1970s through early 2000s. The modern design codes, starting with the 2003 Ordinance, are comparable to contemporary design codes in California (Gazzetta Ufficiale 105, 2003). The most recent Italian design code is the "Norme Tecniche per le Costruzioni" (NTC), which became the legal standard in Italy on July 1st, 2009, right after the L'Aquila Earthquake of April 2009 (NTC, 2008). The 1996 building code was the first to go beyond allowable strength quantities, and considered ductility and deformation compatibility, issues critical to the behavior of structures subjected to lateral seismic loads (NTC, 1996). The most recent seismic-zonation maps were released after the Molise Earthquake of 2002 in the 2003 Ordinance. The fact that most buildings in Italy were built before the 1970s, when the first seismic codes were published, indicates an expected high vulnerability in most existing structures.

Even though the new-construction design criteria in Italy are state-of-the-art, the regulations on retrofit of existing structures are not as rigorous. The issue was first addressed in Unified Italy in building codes in the early 1900 (Royal Decree, 1912). These early building codes, described in detail by Bellicoso in 2011, recommended the replacement of deficient structural components and the placement of metal ties to consolidate vaults and walls, recommending that these ties be spread over a large surface area by incorporating iron plates, long keys, or bars, as shown in Figure 2, Part a (Bellicoso, 2011). These bars are a very common and easily visible form of strengthening in the area hit by the seismic sequence, as shown in Figure 3. Replacement of critical components can often be very costly. This type of strengthening is difficult to identify during earthquake reconnaissance without accessing records.



a. Wall Ties (Vinci, 2014)

b. Reinforced Plaster (Tomazevic, 1999)

c. Repointing (Tomazevic, 1999)

d. Concrete Bond Beam (Tomazevic, 1999)

Figure 2. Seismic Strengthening Techniques

Figure 3. Wall Ties in the town of Visso in May 2017

In 2002 an earthquake struck the region of Molise, in the lower Eastern part of the Italian peninsula. Even though the damage and death toll were moderate, a primary-school collapse, killing 27 children and one teacher, further drew attention to the vulnerability of critical structures in Italy, prompting the Italian government to take action. An Ordinance by the Prime Minister in 2003 stated that the vulnerability of critical buildings had to be assessed in the subsequent five years and provided funding for these evaluations and retrofits, if necessary (Gazzetta Ufficiale, 2003). The critical buildings included schools and hospitals, as well as infrastructure systems in areas of moderate and high seismic hazard. This program does not mandate seismic retrofits, rather provides funding opportunities at the state level for the seismic evaluation and retrofit of schools and government buildings. In addition, because the earthquake occurred in a region that had not been previously classified as a high-seismicity region, the 2003 Ordinance updated the national seismic-zonation maps.

This ordinance provides recommendations on different methods of evaluation as well as indicates possible techniques for strengthening. The strengthening methods are evaluated on the basis of their invasiveness, compatibility, reversibility, durability, and cost. The 2003 Ordinance "suggest[s] adopting minimally invasive but effective techniques such as: inserting cross-ties at suspended floors and building ring beams around the tops of reinforced masonry walls;... strengthening walls by constructing buttresses against them or locally increasing their thickness; ... repointing mortar joints and inserting artificial bonds or transverse ties.” (Bellicoso 2011) These highlighted strengthening techniques, shown in Figure 2, were observed in several buildings during both reconnaissance missions. The three adjacent building units shown in Figure 4 demonstrate the effectiveness of the strengthening methods: the unstrengthened building on the right of the photo, which showed damage after the August 24th Earthquake, collapsed during the October 30th Earthquake. The two buildings to the left of the photos, which appear to be strengthened by re-pointing of the stone masonry, had no observable damage even after the earthquake sequence.

Figure 4. Comparison of buildings with and without re-pointed stone masonry in Illica

The performance-based approach of the 2008 regulations further addresses existing structures by recommending that buildings in historical centers should be evaluated with their adjacent units, blockwise, to take into account the interaction between them and also simplify the calculations (NTC, 2008). The observations of the damage of the 2016-17 indicate that this approach is feasible only if all building owners agree to the retrofit -- adjacent buildings behaved very differently depending on the level of strengthening that had been done to each.

After the 2016-17 Central Italy earthquake sequence, the Italian government initiated a new program, Sisma Bonus, to incentivize structural strengthening in the private sector (Sisma Bonus, 2017). The program consists of providing tax-break incentives to owners who strengthen their building. The amount of tax incentive is proportional to the relative increase in strength of the retrofit. This prescription, thus, requires an initial quantitative engineering evaluation of the existing structure as well as an engineering design and evaluation of the proposed strengthening scheme, which can be costly.

It is worth noting that a shift in paradigm in the early 2000s was important in the definition of retrofit policies. In the early years, the focus was on seismic retrofit. The term retrofit implied the concept of improving a structure to the same level of seismic resistance as new construction. Such a goal would entail significant changes to the structural system and, hence, change the architectural configuration of the structure -- an undesirable outcome for historical buildings. Thus the focus shifted to the concept of "strengthening," which implies a significant improvement in the lateral resistance of a structure without significant changes to the architectural system. This change in paradigm leads to a life-safety/collapse prevention limit state where damage to a structure is acceptable. This performance objective is consistent with the observed response of the residential buildings in the town of Norcia -- many were damaged but very few strengthened ones collapsed. The level of damage to these buildings appears to be proportional to the type of retrofit used, and the quality of the retrofit -- for example, concrete ring beams that were not well anchored into the wall were not effective in maintaining the integrity of the structure.

EFFECTIVENESS OF STRUCTURAL-STRENGTHENING POLICIES AND PRACTICES: COMPARISON OF AMATRICE AND NORCIA

The damage to the historical center of the towns of Amatrice and Norcia is represented by Figure 5. As shown in Table 1, Amatrice is located 9km away from the epicenter of the **M**6.1 August 24th Amatrice Earthquake and 27km from the epicenter of the **M**6.5 October 30th earthquake. Norcia is located 15km from the **M**6.1 earthquake, 5km from the **M**6.5 earthquake. Norcia, being in the central region of the Earthquake Sequence, is also located 13km from the **M**5.9 earthquake of October 26th. Sextos, et al., 2008, have provided detailed building-by-building damage maps for these two municipalities, using the Bray and Stewart damage classification (Bray and Stewart, 2000) (Sextos et al., 2018) and quantified the damage levels, and their progression during the earthquake sequence, for each building. The damage states are given in Table 2. In the town of Amatrice, Sextos et al. indicate that after the Amatrice Earthquake, 30% of the buildings were classified in damage state DS0 (no damage) and 23% in damage state DS5 (collapsed). After the end of the Earthquake sequence, 18% of the buildings were in damage state DS0 and 42% were in damage state DS5, indicating that the Amatrice earthquake caused severe damage to Amatrice, as did the October 30th earthquake. Following the Amatrice earthquake, 97% of the buildings in Norcia were found to have no damage (DS0), and no building collapsed (DS5). At the end of the sequence 67% of the buildings were found to have no damage (DS0), 4% were found to have minor damage (DS1) and 24% of the buildings were found to have moderate damage (DS2) and 3% of the buildings had collapsed (DS5).

Table 2. Damage Classification (Sextos et al. 2018, Bray 2000)

Damage State	Description
DS0	No Damage
DS1	Cracking of non-structural elements, such as dry walls, brick or stucco external cladding
DS2	Major damage to the non-structural elements, such as collapse of a whole masonry infill wall; minor damage to load-bearing elements
DS3	Significant damage to loading-bearing elements, but no collapse
DS4	Partial structural collapse (individual floor or portion of building)
DS5	Full collapse

a. Amatrice, September 2016

b. Norcia, May 2017

Figure 5. Representative Damage in the towns of Amatrice and Norcia

Based on epicentral distances and earthquake magnitude only, the town of Norcia would be expected to have experienced significantly more damage than Amatrice. However, based on available ground-motion data and caused by topographic effects, it was shown that the town of Amatrice experienced much larger significant shaking, especially in the period range of stiff masonry structures, than Norcia during the Amatrice earthquake (GEER, 2016, 2017). However, the disproportionate difference in overall damage states, especially after the October 30th earthquake, whose epicenter was closest to the town of Norcia, may be attributed to ground-motion levels only in part, with differences in building vulnerability accounting for the rest.

The town of Norcia has experienced several devastating earthquakes in the recent past (Figure 6A), with the critical, most damaging earthquake in 1859, after which a building code was first established and implemented in the reconstruction. The city also implemented a proactive strengthening program after a devastating earthquake in 1979 (Ingegneri.info, 2016). The Umbria-Marche earthquake of 1997, whose epicenter was at a moderate distance, served as a testament to the effectiveness of this retrofit program and a reminder of the need to continue strengthening buildings.

The town of Amatrice lies in a region between L'Aquila and Norcia which had not been active in recent social memory. The town was severely damaged both in 1639 and 1703 and rebuilt (at the time Amatrice belonged to the Kingdom of Napoli), but suffered no damage during more recent events, as the epicenters were not near. Amatrice did not experience any earthquake stronger than 7 in intensity according to the Mercalli-Cancani-Sieberg (MCS) scale, as shown in Figure 6B.

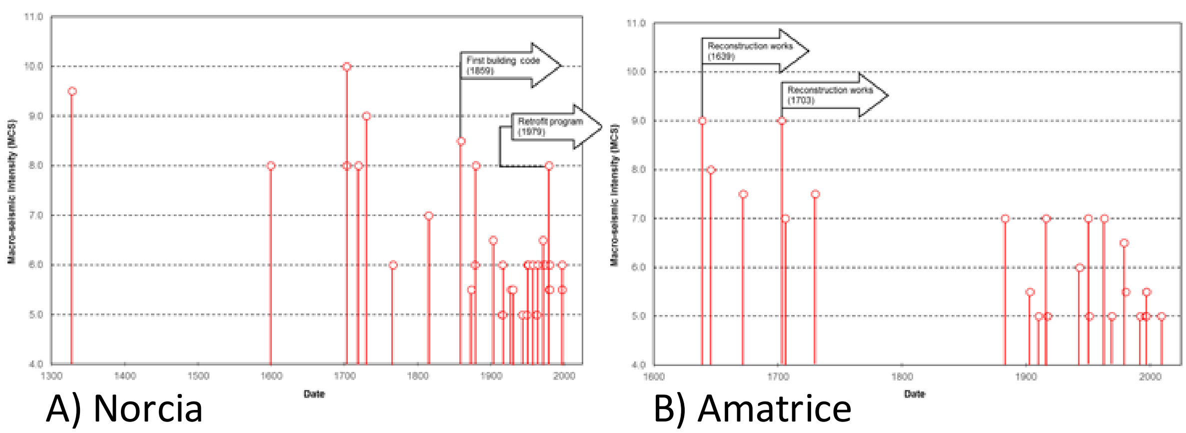


Figure 6. Historical macroseismic intensity (IMCS) of the major events (based on the historical catalogues of earthquakes (Locati, 2011))

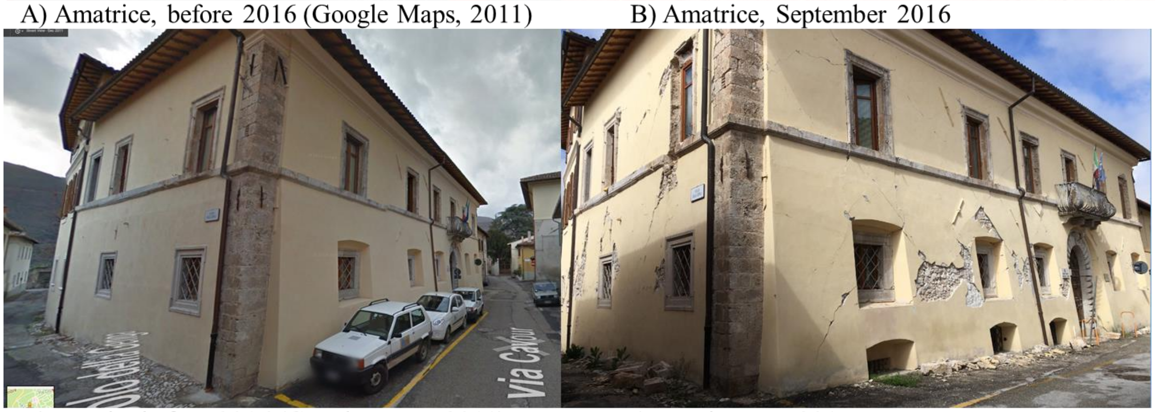
As a result, the building inventory in the town of Amatrice, and its neighboring towns, consisted of many buildings that were built long before any seismic considerations in building construction, nor social awareness of earthquake risk. In addition to having an older building stock built with no consideration of seismic resistance, visible strengthening methods in the town of Amatrice were not as numerous as they were observed in the town of Norcia. The images in Figure 7 compare the residential buildings between the towns of Amatrice and Norcia, respectively. The buildings shown in Figure 7A, in the town of Amatrice, collapsed during the August 24th Earthquake, as shown in Figure 7B. The buildings shown in Figure 7C, in the town of Norcia, showed minimal exterior damage in

May 2017, as shown in Figure 7D. The images show the difference in the construction of these buildings: the height limitations and buttressed walls in Norcia and the lack of these details in Amatrice.

While the historical centers of the two towns are of comparable architecture, the architecture of the periphery areas are different between the towns and more diverse within them. The area on the periphery of Amatrice has three primary building types: low-rise and mid-rise reinforced-concrete moment frames with masonry infills (ductile and non-ductile), large early 20th-century mixed-masonry buildings, and single-family homes. As shown in Figure 8, most of these buildings appear to not have been strengthened and suffered severe damage during the August 24th Amatrice Earthquake.

The periphery of Norcia has more modern construction, with most buildings being low and mid-rise reinforced-concrete frames. The ages of these buildings vary from non-ductile frames to modern buildings under construction, as shown in Figure 9. One area in the periphery of Norcia was damaged during the August 24th Earthquake causing evacuation of a few buildings. Because the site was visited in May 2017 only, it is difficult to attribute the observed damage to a specific event. The residents of this were the first to receive long-term temporary housing because they were the first evacuees of Norcia, as they were evacuated on August 24th. The residential buildings in the periphery of neither Amatrice nor Norcia appear to have been strengthened.

A) Amatrice, before 2016 (Google Maps, 2011) B) Amatrice, September 2016



D) Norcia, before 2016 (Google Maps, 2011) B) Norcia, May 2017

Figure 7. Representative Residential Buildings in the Town of Amatrice and Norcia

Figure 8. Representative Buildings and Damage in Periphery of Amatrice, September 2016

Figure 9. Representative Buildings and Damage in one area in the Periphery of Norcia, May 2017

EFFECTIVENESS OF STRENGTHENING POLICIES IN CRITICAL STRUCTURES

The objective of this section is to give short examples of the observed response of hospitals and schools during the earthquake sequence. The observations made during the reconnaissance effort and shown here are meant to be representative of the whole. However, more detailed and systematic studies need to be made to make the proper assessment and recommendation.

Hospitals

In Amatrice and Norcia, both the hospitals and schools are located outside the historical center, as is typical in this region. The hospital of both towns served the town itself as well as the towns within a 30-50-mile radius. The hospital in Amatrice was damaged during the August 24th earthquake and was evacuated that same day. Figure 10 shows a collage of images from the Amatrice hospital, taken in September 2016. As the figure shows, the hospital is comprised of several wings, each built in different decades -- it is typical of hospitals in this area to grow as the population grows. The different buildings are made of different structural systems and no evidence of strengthening was found. Structural damage was observed in the unreinforced masonry buildings while nonstructural damage was observed in the reinforced-concrete frames.

Figure 10. Amatrice Hospital, September 2016

The hospital in Norcia remained operational after the August earthquake, but was partially evacuated after the October 26th earthquakes, as a precautionary measure because of some minor damage. Patients were moved to the safest parts of the hospital. However, it was further damaged and fully evacuated after the October 30th earthquake. Emergency services were set up immediately in temporary locations nearby. The hospital of Norcia was not visited during either of the reconnaissance missions.

The September 2016 reconnaissance team had the opportunity to visit the hospital in Amandola, shown in Figure 11. Just like the Amatrice hospital, this hospital complex consisted of 4-5 different buildings, with the oldest one being an 18th century unreinforced-masonry building and the newest one was a reinforced-concrete frame with hollow-clay tile infills, completed in 2012. Even though it remained operation by relocating its services to parts of the complex that were considered safe, some buildings in this hospital were severely damaged by the August 24th event, in spite of its significant distance from the epicenter. Most of the damage was nonstructural and concentrated in the building built in the 1980s, hence, likely, designed before seismic regulations. The most significant damage is shown in in Figure 11, where the exterior cladding bricks fell atop an ambulance car. The Amandola Hospital was evacuated and taken out of service after the earthquakes of the end of October

2016. The mayor of the town of Amandola emphasized the importance of maintaining hospitals such as the one in Amandola operational after an earthquake because of the vast territory they serve. Once a hospital becomes out of service, people will need to travel hours to the next nearest hospital.

Figure 11. Hospital in Amandola after August 24th Earthquake

Schools

Schools have been a protagonist in the media during and after the 2016-17 Central-Italy Earthquake Sequence. Initially, because of the collapse of a wing of the Capranica Elementary School in Amatrice on August 24th, they were a symbol of the vulnerability of the built environment and its impact on society (Il Post, 2016). In the reconstruction and recovery period they became a symbol of rebirth, being led by the town of Amatrice (Corriere, 2016). Comparatively, even though it had been strengthened and had only had minimal damage, the school in Norcia was shut indefinitely on October 30th until it has gone through a careful evaluation.

The Capranica school complex in Amatrice was badly damaged during the August 24th earthquake, with one of the wings collapsing, as shown in Figure 12. The school complex had been evaluated and strengthened -- the wing that collapsed had passed the seismic evaluation and did not require strengthening (Il Post, 2016). The school collapse symbolized the socio-economic collapse of the city. With less than one month until the beginning of the school year after the August earthquake, the town of Amatrice was able to repurpose existing prefabricated buildings and took advantage of a research project on prefabricated buildings to be used for school to start school on time (Il Corriere, 2016). The on-time opening of the school in Amatrice brought the community together with a common goal of starting a new chapter. Months later, the town of Norcia has followed the “Amatrice Model” and has opened new long-term temporary school buildings.

Figure 12. Primary-School Collapse in Amatrice, September 2016

The primary school in Norcia was housed in a single building constructed in 1960 and strengthened in 2012 (Fiorentino, 2017). It only had repairable damage to the cladding after the October 30th event, shown in Figure 13A, but was deemed unusable until repairs are done. As shown in Figure 13B, the school building was strengthened using a modern engineered technique with passive dampers whose objective was to reduce lateral deformations. Even though the school buildings in the towns of Amatrice and Norcia behaved differently, the end result was the same for the two schools -- students were relocated to new long-term temporary school buildings.

Figure 13. Primary School in Norcia, May 2017

EFFECTIVENESS OF STRENGTHENING METHODOLOGIES

Unreinforced Masonry

Unreinforced stone/brick masonry structures represent a large percentage of the building stock in the historical center of Italian towns. They are prevalent in the historical centers throughout Italy, likely because of their thermal-insulation properties and because of the readily-available building materials. These buildings have structural characteristics of being stiff and heavy, but can be brittle when subjected to seismic lateral loads if they are not detailed properly -- the heavy components need to maintain their integrity and work together like a box.

Figure 14 shows four different buildings with different levels of strengthening and different responses, not all consistent with what would be expected from the level of strengthening. Building A, located in Accumoli, collapsed during the August 24th earthquake even though it had been strengthened using several steel ties that spanned the length of the building. A careful observation of the rubble shows that the poor quality of the mortar did not maintain the integrity of the walls which must have collapsed under their own weight as soon as they began deforming out of plane, as has been observed in similar structures.

The strengthened building labelled Building B, also located in Accumoli, appears to have sustained the entire earthquake sequence without any visible damage. The number and distribution of steel ties, as well as the quality of the mortar on the side of the building and the fine stonework in the front of the building show that a well-engineered strengthening will achieve the desired performance goal. This building, however, was evacuated and cannot be used because the entire town of Accumoli was collapsed around it.

Figure 14. Strengthened Stone Masonry Buildings

The building labelled Building C shows a building in the center Accumoli in May 2017 where it is evident that the only strengthening measure that was applied to the building are steel ties, both old (small) and new (large), and repointing of the corners. The façade of this building was not damaged after the Amatrice Earthquake. Even though the facade of the building collapsed during the October 30th event, it was not a total building collapse. The steel ties and the repointing maintained the integrity of the corners of the buildings, but the wall facade did not maintain its integrity and was not anchored to the building corners. Building D is not located in Accumoli, as the other buildings are, but is shown as another building where it is evident that tie rods placed at critical locations reduce damage to the structure. The horizontal crack at the corner of the roof level and the lack of steel ties at that level, indicate that a concrete ring beam may have been placed there. The ring beam did maintain the integrity of the roof level, but this ring beam was not well anchored to the top floor, where damage is most evident.

The most basic type of strengthening is via grout injection into the wall mortar, known as repointing. The objective of grout injection is to restore the original integrity of the retrofitted wall and to fill the voids and cracks, which are present in the masonry due to physical and chemical deterioration and/or mechanical actions. Injected mortar can be effective in restoring the initial stiffness and strength of masonry. However, this strengthening technique is not very effective in improving the in-plane lateral response and should be combined with reinforced plaster or steel rods.

A strengthening strategy that was popular in Italy in the 1980s was the placement of a concrete ring beam at the roof level, as well as the use of stiff concrete roofs expected to provide rigid-diaphragm action. Several buildings that implemented this retrofit measure in Amatrice collapsed during the Amatrice Earthquake, as shown in Figure 15. The main problems with this type of strengthening are twofold: 1. The higher mass at the roof draws additional destabilizing inertial forces, and 2. The higher stiffness of the RC beam or roof combined with an inadequate connection to the underlying masonry, may induce an out-of-plane bending of walls between the restraining floors during a seismic event, causing a partial collapse, as was observed in many buildings. The graphic in Figure 15 shows a representation of the distribution of vertical stresses: the border edges are subjected to higher confining vertical stresses (dark color), while these confining stresses reduce to zero (white) in the upper center region of the wall. This schematic is consistent with observed damage, shown in many figures in this paper.

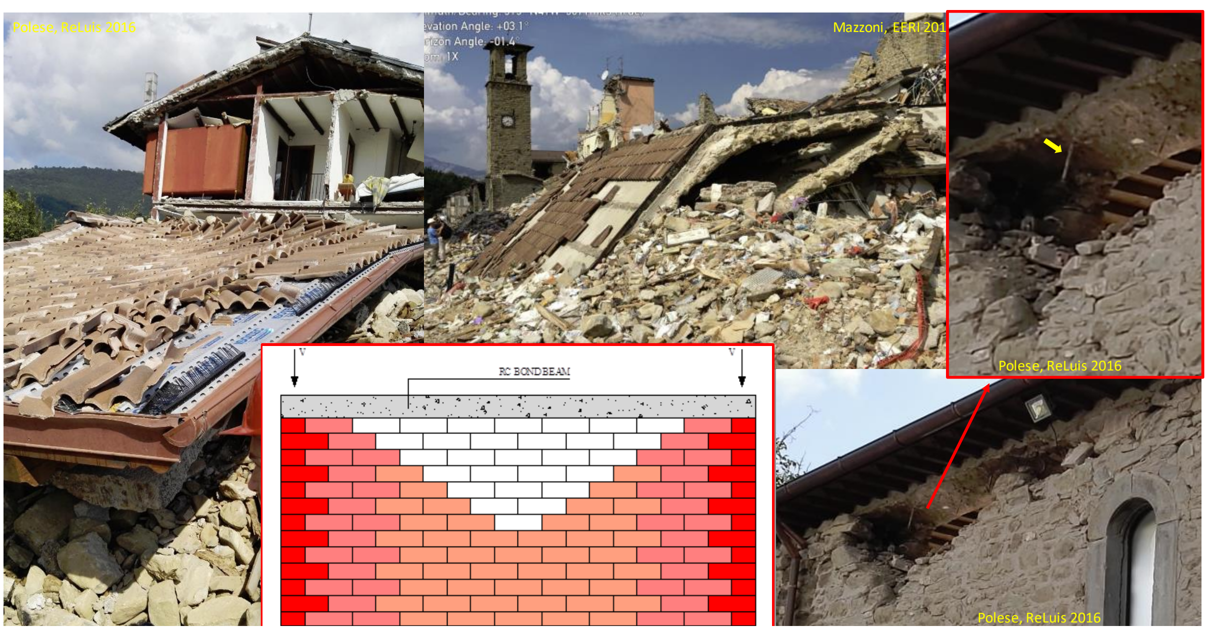


Figure 15. Examples of anchorage failure in Ring-Beam Retrofit

Because of its minimal cost and its effectiveness, the application of reinforced (steel mesh) plaster to interior and/or exterior walls is the most common type of strengthening methodology. It is typically combined with grout injection to improve combined action with the wall itself. This strengthening methodology, can be recognized by the contrast between the exposed stonework at the corners and the thicker plaster. Buildings with this characteristic are numerous in Norcia and they are easy to distinguish from those that look aged. Figure 16 shows Hotel Seneca, a historic-building hotel in the historical center of Norcia near the main square. The reinforced plaster was added to both exterior and interior walls, as shown in the figure, noticing its contrast, and additional thickness, with respect to the original stonework. It is worth noting the presence of steel ties that span both directions of the building (actually a pair of buildings). There are two types of ties present, some may have been there well before the latest strengthening, some appear to be more recent. Palazzo Seneca was strengthened before 2016 and did not sustain any damage during the earthquakes. Because the entire historical center of Norcia was evacuated, the Hotel had to shut down and did not reopen for business until circa April 2017. Because it is the least invasive procedure, reinforced plaster, with grout injection if necessary, appears to be the most common strengthening methodology in Norcia.

Figure 16. Example of Strengthening with Reinforced Plaster, Hotel Seneca in Norcia

Reinforced Concrete Structures

Reinforced-Concrete (RC) structures in Italy are typically found outside of the historical parts of town and represent the relatively-modern inventory of residential buildings. Several reinforced concrete buildings in Norcia were evacuated after the August 24^{th} Amatrice Earthquake. The vulnerability of RC structures is a very important component of the vulnerability of a region because of their higher population content. In addition to residential apartment buildings, many hotels in the region affected by earthquake sequence of 2016-17 became inaccessible, thus having a significant impact on tourism, an important component of the regional economy.

Figure 17 shows a representative RC buildings and typical damage due to earthquake. Because it is a mountainous region, RC frames are insulated using two layers of hollow clay tile or bricks, with the outer layer often being part of the cladding. During lateral shaking the deformation incompatibility between the flexible frame and the stiff infill cause the infill to fail either in plane or fall out of plane, as shown in the figure. Even though this type of response mechanism may not lead to structural failure, the damage to the nonstructural components makes the building unusable. There are cases, also, where the deformations are large enough and the infill masonry is stiff enough to cause damage to the nonductile concrete columns and/or joints, as shown in Figure 18.

Figure 17. Representative Reinforced-Concrete Building in Norcia

Figure 18. Damage to Non-Ductile Reinforced-Concrete Frame in Amatrice

One technique that was used to strengthen a reinforced-concrete frame building was the use of passive dampers in a school in Norcia, shown in Figure 13. The passive dampers were effective in reducing lateral deformations of the frame thus preventing structural and minimizing non-structural damage (Fiorentino et al., 2017). This strengthening technique is significantly more expensive and invasive than those presented earlier in this paper. It is, however, the most effective, and least invasive, strengthening technique for reinforced-concrete structures. The nonstructural damage to this school shows that a strengthening scheme must be consider both structural and nonstructural components.

CONCLUSIONS

The observations presented in this paper indicate that minimizing damage to existing structures during an earthquake is a technical issue. These observations also indicate that minimizing damage to a region is a policy issue requiring a commitment from both the government and the community. The low damage state in most of the town of Norcia after the earthquake sequence showed that consistent implementation of strengthening practices across a building inventory is effective in earthquake-damage mitigation. These strengthening methodologies maintained the integrity of the brittle structures to be able to withstand a sequence of earthquakes of moderate magnitudes.

The fact that the Central-Italy Earthquake Sequence of 2016-17 lasted more than six months and affected several regions and municipalities, each in a different way, served as a parametric demonstration on preparedness. The town of Amatrice was hit hard by an earthquake of moderate magnitude and close distance, with numerous structural collapses in the town itself and its neighboring region, including Accumoli and Illica. Additional buildings collapsed during the subsequent earthquake of larger magnitude, but also larger distance. The town of Norcia was minimally affected by the earthquake near Amatrice and suffered moderate damage during the largest-magnitude event at a very close distance. After the seismic sequence had subsided, six months after the first significant earthquake, the town of Amatrice was left in ruins, while the town of Norcia had begun to repopulate. The key reason for this difference is the fact that Norcia had suffered damaging earthquakes in the past, thus it implemented stronger seismic criteria in its past reconstructions. The town of Amatrice, on the other hand, had not had significant earthquakes in recent history and, thus, had a much more vulnerable building stock.

The significant damage to school and hospitals in the regions affected by earthquake sequence, on the other hand, has demonstrated that a more rigorous approach of evaluation and strengthening must be implemented for critical structures at the regional level. The regional hospitals' failure to remain operation after the design-level events because none of them had been strengthened, indicate that government regulations need to require seismic upgrade of critical structures, not just incentivize it. The observed damage and lessons learned from the Central-Italy Earthquake Sequence of 2016-17, however, have shown that the strengthening must focus on nonstructural as well as structural functionality of a critical facility if continued operation is desired after a design-level event.

In addition, mitigation policies need to be developed for modern RC structures where damage to non-structural components renders a building unusable and displaces a large population, especially in hotels and other service buildings, having a significant negative effect the local economy.

The few undamaged strengthened buildings in the towns of Amatrice and Accumoli highlight the need for a community-wide collaboration effort in strengthening policies. Individual owners have little incentive to invest their savings if their building is the only one left in standing in the town. This issue has been observed in many earthquakes in the past.

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