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THE 2016 CENTRAL ITALY EARTHQUAKE SEQUENCE: OBSERVATIONS OF INCREMENTAL BUILDING DAMAGE

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ABSTRACT

A sequence of normal-fault earthquakes occurred between the end of August 2016 and the end of October 2016 in central Italy causing significant damage and major disruption in a wide area covering several municipalities across four regions, Abruzzo, Lazio, Marche, and Umbria. The sequence of events is composed of five events with magnitude greater than M_w 5, two of which with magnitude greater than M_w 6. The last October event is the strongest event since the 1980 Italian Irpinia event. The building portfolio in the affected area was not particularly resistant to intense ground shaking, resulting in the collapse and heavy damage of several buildings and in tens of thousands of homeless. To study the damage induced by the earthquakes sequence, two international missions were organized by the Geotechnical Extreme Events Reconnaissance (GEER) group after the first and the last seismic event. The consistent and detailed inspection of structural damage to buildings after a single and a sequence of events, constitutes a precious case study for examining the evolution of structural damage of different structural systems to a series of ground motions. It further underlines the high vulnerability of a part of the Italian building stock, especially under multiple shocks, and opens the floor for discussing the design implications of cumulative damage.

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The 2016 Central Italy Earthquake Sequence: Observations of Incremental Building Damage

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ABSTRACT

A sequence of normal-fault earthquakes occurred between the end of August 2016 and the end of October 2016 in central Italy causing significant damage and major disruption in a wide area covering several municipalities across four regions, Abruzzo, Lazio, Marche, and Umbria. The sequence of events is composed of five events with magnitude greater than $M_w 5$, two of which with magnitude greater than $M_w 6$. The last October event is the strongest event since the 1980 Italian Irpinia event. The building portfolio in the affected area was not particularly resistant to intense ground shaking, resulting in the collapse and heavy damage of several buildings and in tens of thousands of homeless. To study the damage induced by the earthquakes sequence, two international missions were organized by the Geotechnical Extreme Events Reconnaissance (GEER) group after the first and the last seismic event. The consistent and detailed inspection of structural damage to buildings after a single and a sequence of events, constitutes a precious case study for examining the evolution of structural damage of different structural systems to a series of ground motions. It further underlines the high vulnerability of a part of the Italian building stock, especially under multiple shocks, and opens the floor for discussing the design implications of cumulative damage.

Introduction

Between the 24th of August 2016 and the end the 30th of October 2016 three major earthquakes occurred in Central Italy damaging several villages and leaving about 30000 displaced people: the first $M_w 6.1$ Amatrice earthquake struck on the 24th of August, 2016 at 01:36 UTC [1]; two months

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later, two more events followed. i.e., the M_w 5.9 Ussita earthquake occurred on the 26th of October 2016, at 19.18 UTC, and the M_w 6.5 Norcia event on 30th of October 2016, at 06.40 UTC [2]. The latter was the strongest seismic event in Italy since the M_w 6.9 Irpinia earthquake, which occurred on 23rd of November 1980 [3].

Figure 1 shows the epicenters of the events with magnitude greater than M_w 5.0 in the period between the 24th of August and the 30th of October 2016. The first shock was followed by an intense M_w 5.3 earthquake the same day, and the second shock was preceded by an M_w 5.4 earthquake. On the same figure, the Colfiorito-Campotosto composite seismogenic source (indicated by the red line) is also represented. Notably, the three activated faults highlighted by the black rectangles fall in the above seismogenetic context.

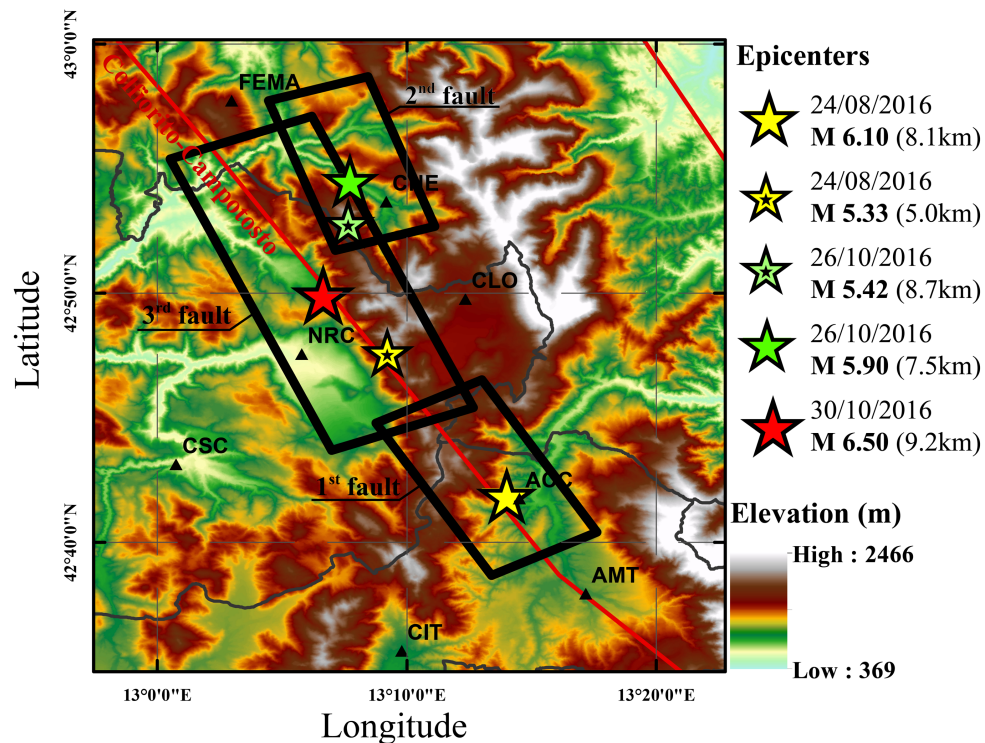


Figure 1. Epicenters of events with magnitude greater than 5, recording stations, faults projections, and composite seismogenic source Colfiorito-Campotosto.

A wide geographical area among the boundaries of Abruzzo, Lazio, Marche, and Umbria regions was affected in terms of structural and geotechnical damage. This area had been identified as a seismic gap zone [4,5], given that it is located between the 1997 M_w 6.0 Umbria-Marche epicenter to the north and the 2009 M_w 6.3 L'Aquila epicenter to the south. Specifically, the last significant earthquakes reported in this area were the M_w 6.2 Amatrice earthquake in 1639, the 1703 sequence of two main events of magnitude 6.9 and 6.7, respectively, and the M_w 5.6 Norcia earthquake in 1859 [6]. Such seismic gap consisted in a serious threat for all structures, particularly to the substandard, historical, residential buildings constructed in the last hundreds of years, well before modern specific codes were implemented.

The municipalities of Accumuli, Amatrice, Arquata del Tronto, Castelsantangelo sul Nera, Norcia, Preci, Ussita and Visso are the ones that were more severely affected by the 2016 seismic sequence [7,8]. To investigate the structural damage, after the search and rescue operations, two

field missions were organized in the early October 2016 and early December of the same year. The two missions were coordinated by the Geotechnical Extreme Events Reconnaissance (GEER). Among the affected hamlets, the two missions focused on the municipalities of Accumoli, Amatrice, and Norcia. An overview of the GEER missions' activities can be found in the series of dedicated reconnaissance reports released in early 2017 [9-11].

After the deployment of the two field missions, inspection data were post-processed, enriched and critically assessed. This work presents how the damaged evolved from one event to the other both at meso- (city level) and micro- (building level) scales. The classification of damage was conducted according to Grunthal [12], while particular attention was paid to the potential correlation between local topography and structural damage observed.

Spectral characteristics of the events

Not all the recording stations in the area were fully functional when the major events occurred; therefore, with respect to the surveyed municipalities, only the stations belonging to the RAN Italian strong motion network located in Amatrice (AMT) and Norcia (NRC) are considered herein. Unprocessed records are freely available on the RAN website; meanwhile corrected records and processing details are available on the Engineering Strong-Motion (ESM) database [13]. Figure 2 shows the response spectra of the signals that were recorded in Amatrice (Fig. 2a, 2b) and Norcia (Fig. 2c, 2d) after the first and the second event, for both components, i.e. East-West (in blue) and North-South (in red).

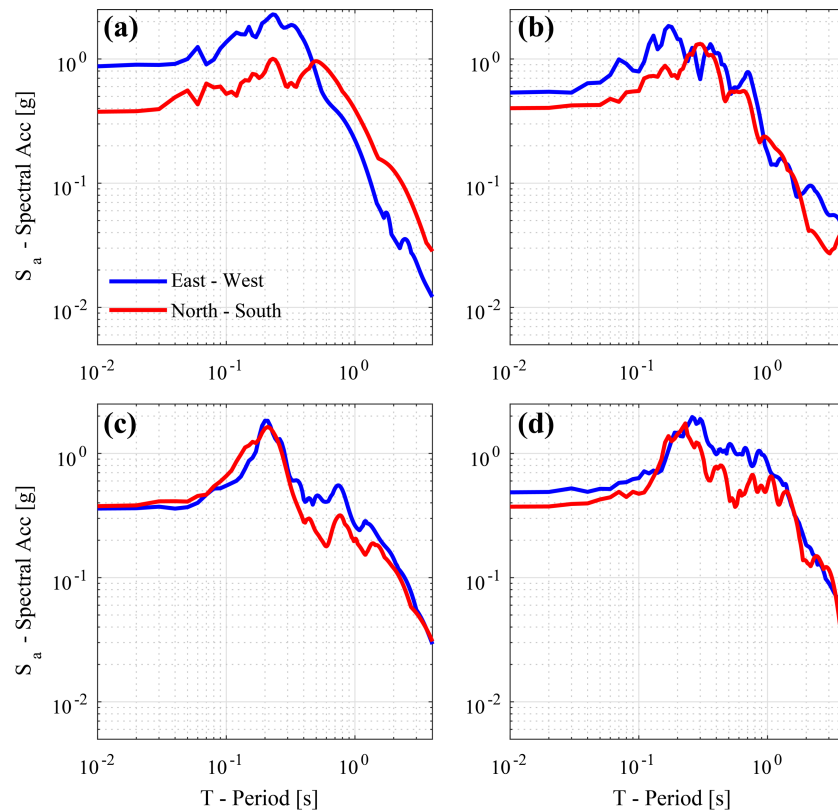


Figure 2. Spectra of the signal of the first (a,c) and last (b,d) seismic events, recorded at Amatrice (a,b) and Norcia (c,d) accelerometric stations.

It is observed that for the case of Amatrice, the spectra associated with the EW direction are in general predominant compared to the NS component, except for the long period range and the first seismic event. No specific differences between the two directions can be identified for the case of Norcia. It is also seen that for both stations, the maximum amplification is obtained in the short period range (i.e., $0.1s \div 0.5s$). It is only for the 30th October event, that a moderate spectral amplification is also observed in the medium period range of $0.5s \div 1.0s$.

Geological and topographical characteristic of the affected area

Data processing after the sequence of earthquake events has shown that the structural damage in various hamlets and villages is closely correlated with local site effects [14]. According to the 1:500,000 Italian geological map, the geological bedrock in Accumuli and Amatrice is made of sedimentary lithology units composed of sandstones and clay lithofacies of the late Miocene, while the geological bedrock in Norcia is composed by unconsolidated colluvial, terraced alluvial, fluviolacustrine and fluviglacial deposits of Pleistocene. Figure 3 illustrates the slope maps obtained on the basis of a 20m resolution digital elevation model for Accumuli, Amatrice and Norcia. It can be observed that due to the ridge-type local topography in Accumuli, topographic amplifications are likely to have occurred. Similarly, the slope map of the region of Amatrice indicates a sharp hill border which is also probable to have led to local site amplification to some extent. On the contrary, the slope map in the area of Norcia shows that the valley is flat and that topographic effects are not expected.

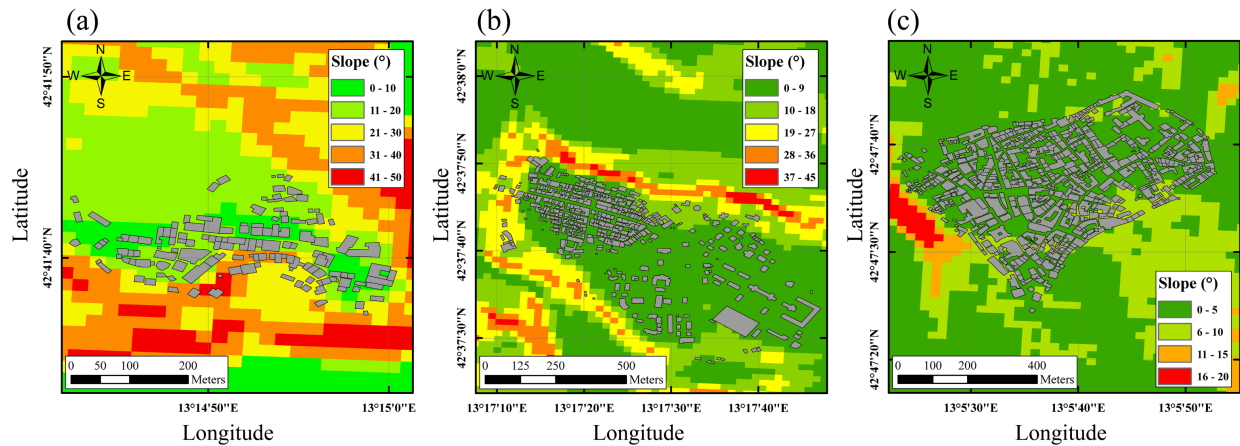


Figure 3. Slope maps for (a) Accumuli, (b) Amatrice, and (c) Norcia. The grey rectangles represent the surveyed buildings.

Meso-scale damage observation

As already discussed, this study focuses on three characteristic municipalities only, namely Accumuli, Norcia and Amatrice, for which a consistent dataset was formed after the two major events. A total number of 1,172 building were observed and analyzed. Notably, more than 95% of buildings were unreinforced masonry (URM) structures with the few reinforced concrete buildings being located in the perimeter of the Amatrice historical center. According to latest 2011 Italian

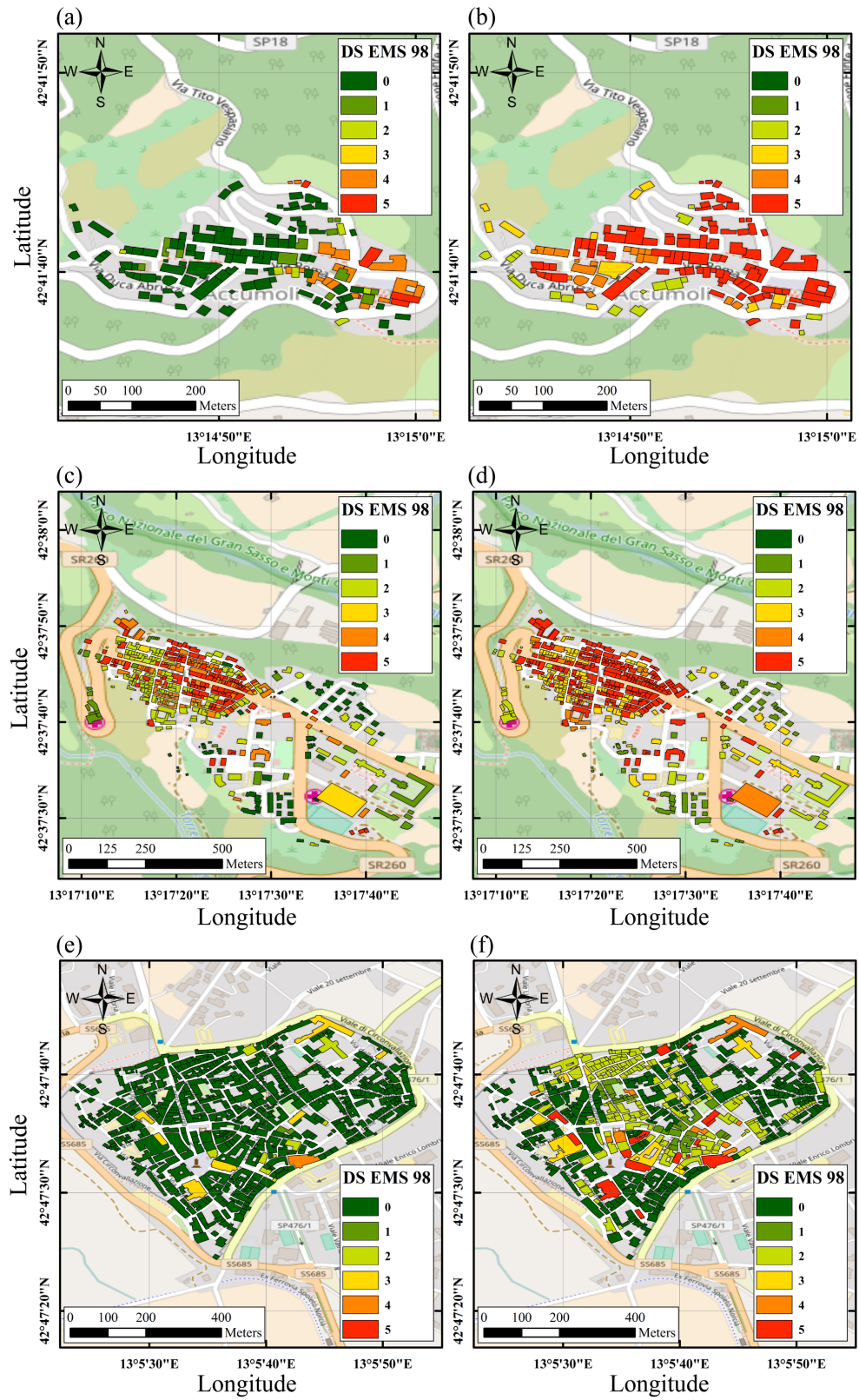


Figure 4. Damage observed in (a,b) Accumoli, (b,c) Amatrice, and (c,d) Norcia during the first (a,c,e) and the second (b,d,f) survey, respectively.

census, the building portfolio was mainly composed by old, two to three-story buildings that were constructed more than hundred years ago but were reported as having a good or “optimum” status of conservation. Figure 4 shows the structural damage assessed in terms of EMS 98 [12], as it was observed during the two surveys in Accumuli, Amatrice, and Norcia. The first two show an abrupt increase of structural damage under multiple earthquake events, while most buildings in Norcia retain a residual level of capacity. In all cases though, it is observed that structural damage of URM buildings does not follow a linear pattern of increase but accumulates disproportionately during multiple earthquake excitations due to the inherently brittle nature of masonry and the lack of appropriate retrofit measures. In regions such as Norcia where some retrofit schemes had been applied, the above degree of damage increase is relatively lower. Overall the following variation of damage have been observed after the first and the third major earthquake events: from 65.4% to 38.7% for DS0 (no damage), 2% to 2.3% for DS1 (minor damage), 11.9% to 16.2% for DS2 (minor-to-moderate damage), 0.6% to 11% for DS3 (moderate-to-major damage), 9.1% to 3.1% for DS4 (major damage), and a major shift from 11% to 28.7% for DS5 (collapse).

Correlation between damage and topography

To understand whether there is a correlation between the observed damage and the local topography the rank correlation was calculated by means of the Sperman’s rho [15]. More specifically, for each building an intersection between the building footprints and the slope maps has been carried out. The slope value was then analyzed with respect to the damage state classification that was reported during inspection leading to a positive correlation of 0.19 and 0.38 for the first and the second survey, respectively. This observation indicates that the slope is potentially a useful proxy of the spatial distribution of damage. Figure 5 shows in more detail the distribution of the damage states as function of the local slope. It is possible to observe that when the slope increases, the frequency of occurrence of higher damage states also increases, thus highlighting the correlation between damage and topography for the case of the three towns examined.

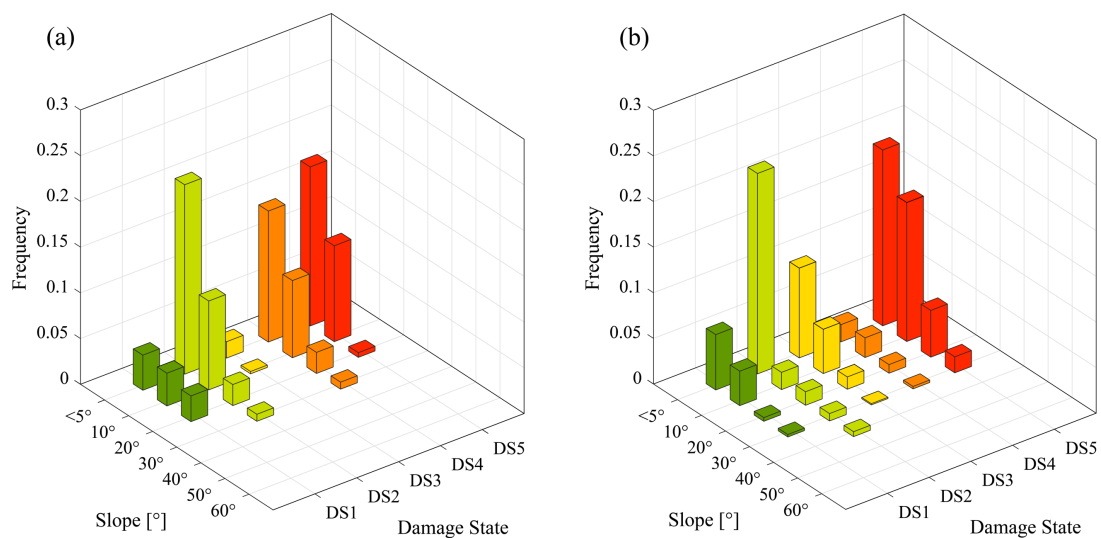


Figure 5. Damage as function of the local slope; (a) after the first event and (b) after the entire sequence.

Micro-scale damage observation

The typical evolution of damage on masonry buildings is shown in Figure 6, depicting a typical heritage building in Amatrice that experienced an incipient out-of-plane mechanism of the façade after the first shock, and eventually collapsed after the entire sequence. This is an example of a rapid evolution of damage during successive earthquake events that was very common in the case of Amatrice. Contrary to the previous observation, Figure 7 shows the evolution of damage for a masonry residential building in Norcia where a small increase of previously formed cracks can only be observed. This confirms that the evolution of cumulative damage of residential masonry buildings depends on the degree of repair and/or retrofitting measures that have been implemented, Norcia being a good example given the strengthening works (i.e., reinforced mortar, buttresses and connecting steel ties) that took place after the 1997 Umbria-Marche.



Figure 6. Masonry church in Amatrice after the (a) first and (b) second survey.

In contrast to conventional buildings in the town of Norcia, heritage structures and particularly churches, suffered major damage or collapse at the end of the seismic sequence. This fact can be attributed to two main reasons: (a) such structures have generally moderate to long period since they are commonly tall and long thus being quite flexible laterally, and (b) the events that followed the first one also amplified the moderate period range (Fig. 2), hence considerably increased the seismic demand in the particular range of periods of interest.

Overall, and perhaps with the exception of structures that had been previously repaired and/or strengthened, it is evident that masonry buildings suffered, on average, significant and disproportional damage increase during the sequence of seismic events, due to their low residual capacity and the brittle nature of the failure modes involved, thus quickly shifting from low-to-moderate damage states (DS1-DS3) to full collapse (DS5).

As already mentioned, the majority of the buildings inspected were reinforced and unreinforced masonry ones. An interesting case is also reported herein of a multi-story steel moment-resisting frame (MRF) building that survived the multiple seismic excitations within

Amatrice's historical center (Figure 8). It was built in the early 90's according to the 1996 Italian seismic code [16] and consists of a basement, the ground floor, and two upper stories alongside a shorter top story that serves as a penthouse. More details about its structural and dynamic characteristics as well as the assessment of its seismic performance during the sequence of events can be found in [17]. After the 24 August event, the building mainly suffered cracks in the infill panels, with only small local flange instabilities observed at the top of two front columns of the ground floor. At the end of the entire seismic sequence, the building experienced evident permanent deformation along its longer direction, as shown in Figure 8. Such permanent deformation was localized at the second level of the building with a visible residual inter-story drift due to the relative positions of infills and openings. Preliminary finite element analyses of the building confirmed that the fundamental period of the structure is approximately equal to 0.75sec. This was an uncoupled translational mode along the long side, which was mainly attributed to the orientation of the steel columns with their strong axes aligned with the short side of the building. Naturally, residual drift developed along the longitudinal (weak) axis.

(a)



(b)



Figure 7. Masonry residential building (a) after the first earthquake and (c) after the entire sequence.

(a)



(b)



Figure 8. Steel residential building (a) after the first earthquake and (b) after the entire sequence. (a) Limited non-structural damage and (d) complete non-structural damage at ground level with consequent residual drift.

Reinforced concrete buildings, mainly suffered typical out-of-plane collapse of the infills, cracks in the beam-column joints and sporadic shear failures. Concrete spalling and buckling of longitudinal rebars was also observed. Even though the general trend was that damage in R/C buildings built up slower than in the case of masonry structures under multiple earthquake events, there were few cases where damage accumulation was abrupt. An example is the residential RC building in Norcia depicted in Figure 9 which only suffered shear failure in a single column after the first event, but experienced soft-story collapse during the third event. This was due to its high irregularity in both elevation and plan as well as its inadequate transverse reinforcement. Failure of such irregular buildings is common in Italy, as exemplified in the work of Verderame et al. [18].

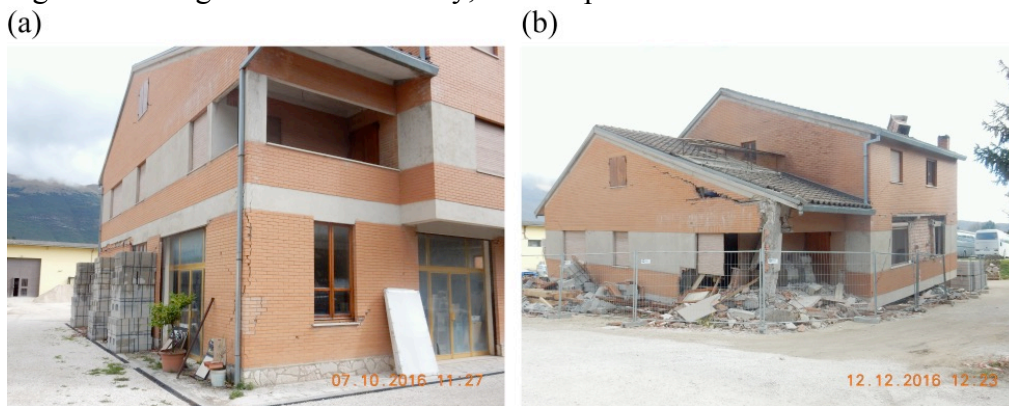


Figure 9. Reinforced concrete residential building (a) after the first earthquake and (b) after the entire sequence.

Conclusions

In 2016, a sequence of five earthquakes with magnitude greater than 5 and hundreds of low magnitude shocks struck central Italy. The first event of August 2016 caused casualties, structural damage, geotechnical failures, and business interruption in a wide area spanning among four regions, namely, Abruzzo, Lazio, Marche, and Umbria. A GEER coordinated field mission was deployed twice, once in early October 2016, that is, after the first shock, and once in early December, after last main shock. A detailed visual inspection scheme was developed for Accumuli, Amatrice, and Norcia, acquiring consistent samples of structural performance and cumulative damage for the same building portfolio after (a) a single and (b) the entire sequence of earthquake events. The damage extent and failure patterns observed correlated well with the slope spatial distribution thus highlighting the potential of local site topographic effects. Additionally, as it is commonly the case, the age of construction, the frequency content of the ground motion and the variation of spectral polarization across several events further correlates to the severe damage distribution across several Municipalities.

The majority of the buildings inspected showed a clear evolution of damage after multiple earthquake excitations irrespectively of their structural system. However, the degree of damage accumulation under repeated ground motions was different. For instance, reinforced concrete buildings did not experience disproportional damage under multiple events, generally demonstrating adequate ductility. As a result, their damage at a system level remained approximately constant or slightly increased from the first earthquake until the end of the sequence. Masonry structures on the other hand, suffered significant damage during the first event and quite often experienced an abrupt increase of damage from D1-D2 to major damage (D4) or even

collapse (D5) after a successive earthquake due to their rapidly reducing residual capacity and their brittle nature. Local retrofit with steel ties at the corners of the upper story prevented further damage and collapse in a number of cases, particularly within the town of Norcia where several structures had been strengthened in the last two decades. Local interventions limited on the ground level alone, however, were shown to be insufficient. This is because the reduced axial load and the weak diaphragm action of the masonry walls at higher levels may lead to extensive shear and out-of-plane failure at the upper stories, respectively. Even though the three towns studied (Accumoli, Amatrice, and Norcia) are not directly comparable as they were exposed to different levels of ground shaking over the earthquake sequence, the overall assessment is that reinforced masonry performed significantly better than the unreinforced ones and that simple measures such as ties and buttresses may be proven crucial to prevent structural collapse.

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