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NON-STRUCTURAL AND STRUCTURAL DAMAGE INDUCED BY THE 2016 CENTRAL ITALY AMATRICE (AUGUST 24, M_w=6.2) AND NORCIA (OCTOBER 30, M_w=6.5) EARTHQUAKES

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ABSTRACT

On August 24, 2016 an Mw=6.2 earthquake struck Amatrice basin (Central Apennines, Italy) resulting in 299 fatalities, 388 injuries and about 3000 homeless. On October 30, 2016 an Mw=6.5 earthquake occurred in Norcia basin with no fatalities due to building evacuation of the affected area after prior events on October 26. Based on our field reconnaissance in the affected area immediately after each earthquake, the following conclusions can be drawn. The dominant types of structures are (a) reinforced concrete (R/C) and (b) unreinforced masonry (URM) buildings dated back as far as medieval times. Both earthquakes resulted severe structural and non-structural damage in buildings in the Amatrice, Campotosto, Castellucio and Norcia intermontane basins. Damage to R/C buildings were due to (a) poor quality of concrete with compressional strength lower than the expected and inadequate reinforcement, (b) absence of earthquake resistant features even in recent constructions, (c) inappropriate foundation close to the edge of the slopes of flat hills that also leads to differential settlements creating cracks homologous to those seismically induced and (d) the destructive effect of the vertical component of the earthquake ground motion. Damage to URM buildings are attributed to (a) the poor workmanship with randomly placed materials of poor and inadequate quality bound by low-strength mortars and without antiseismic precautions, (b) the effect of the vertical component of ground motion to buildings as well as (c) inadequate interventions and modifications after previous earthquake damage. It is concluded that the observed damage are typical of shallow normal-faulting near-field earthquakes.

Keywords: 2016 Amatrice earthquake; 2016 Norcia earthquake; Central Apennines; seismic response; structural damage

1. INTRODUCTION

At the dawn of Monday 24 August 2016 (01:36:33 UTC; 03:36:33 local time) a strong Mw 6.0 earthquake struck Central Italy (Anzidei and Pondrelli, 2016; Lavecchia et al., 2016; Tinti et al., 2016). This earthquake, known as the Amatrice earthquake, was predominantly felt on the Umbria, Marche, Abruzzo and Lazio regions resulting in 299 fatalities, more than 380 injuries and about 4500 homeless in villages in the borders of Marche and Lazio regions (Galli et al., 2016). The epicenter is located in the area between Vettore and Laga Mts, about 12 km NW of Amatrice town (Anzidei and Pondrelli, 2016; Lavecchia et al., 2016; Tinti et al., 2016). The main shock was located at the depth of 8 km and the provided moment tensor solutions demonstrated a NW-SE striking and SW-dipping normal fault (Gruppo di Lavoro INGV sul terremoto di Amatrice, 2016; Tinti et al. 2016). The largest

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aftershock occurred one hour after the main shock with Mw 5.4 and depth of 8.7 km, while three aftershocks with M_w varying from 4.3 to 4.8 were generated during the first three days of the aftershock sequence.
This event marked the initiation of a prolonged earthquake sequence that continued until the early 2017. It was characterized by the generation of three large events, a moderate Mw 5.4 earthquake with depth of 9.3 km and a strong Mw 5.9 earthquake with depth of 8.4 km on October 26, 2016 at 17:10:36 UTC and 19:18:05 UTC respectively and a strong Mw 6.5 earthquake, known as the Norcia earthquake, with depth of 9.4 km on October 30, 2016 at 6:40:17 UTC (Gruppo di Lavoro INGV sul Terremoto in Centro Italia, 2016). These events were accompanied by more than 60000 aftershocks-foreshocks (Scognamiglio et al., 2016; Chiaraluce et al., 2017). Based on the assessed magnitudes, the last Mw 6.5 earthquake could be considered as the main event, while the others as foreshocks. Moreover, the Mw 6.5 earthquake was the largest seismic event occurred in the Italian peninsula since the devastating Ms 6.9 1980 Irpinia earthquake (Westaway and Jackson, 1987).
The aim of this paper is the brief presentation of the geological and seismotectonic setting of the affected area in the Central Apennines and the extended description of the non-structural and structural damage induced by the Amatrice and Norcia earthquakes, the largest of this sequence, based on macroseismic observations recorded during field reconnaissance conducted in the affected area by the authors immediately after each earthquake.

2. GEOLOGICAL SETTING OF CENTRAL APENNINES

The study area is located in the Umbria-Abruzzi Apennines and affected by the Central Apennines fault system has been developed along the axial zone of the Apennines.

2.1. The Central Apennines Fault System

The Central Apennines fault system (CAFS) is a coherent fault network developed in response to a remote stress field acting in the area since the Middle Pleistocene (Cello et al., 1995). It comprises N-S striking left-lateral strike-slip, transtentional and NNW-SSE to WNW-ESE striking normal faults resulted from a stress field characterized by a sub-horizontal, NW-SE trending maximum compression and from a NE-SW oriented extension (Cello et al., 1997). These faults are not only reactivated but also newly-formed faults constituting a 30-50-km-wide and a 100-km-long fault zone extending from Camerino in the north to L’ Aquila in the south (Cello et al., 1997; Galadini and Galli et al., 2000). They also dissect or invert pre-existing features of the Central Apennines fold and thrust belt (Calamita et al., 1994a and references therein) and bound mountainous intermontane basins infilled with Pleistocene-Holocene deposits (Galadini and Galli et al., 2000; 2003). The recent tectonic activity of some of these faults is indicated by the occurrence of fault scarps affecting both bedrock and Quaternary deposits.
This Central Apennines fault system is made up of three major fault sets: (a) the Colfiorito - Leonessa, (b) the Monte Vettore - Gorzano and (c) the Norcia - L’Aquila sets. They can be related to regional strike-slip deformation and to the development of a composite negative flower structure including these major fault sets which, all together, represent the surface expression of a crustal scale left-lateral shear zone roughly trending north-south (Cello et al., 1997 and references therein).

2.2. Active faults surrounding the affected area

The major active structures in the Umbria-Abruzzi Apennines are Late Pleistocene - Holocene primary dip-slip (normal) and oblique-slip (left-lateral) faults which belong to the Central Apennine Faults System (CAFS) and either bound the main intermontane basins or are responsible for the formation of minor basins in mountainous areas (Galadini and Galli, 2000 and references therein). Their prolongations into mountainous areas have resulted in bedrock usually carbonate fault scarps which, however, are not diagnostic of Late Pleistocene - Holocene activity (Bosi et al., 1993). The faults, which are active during the last millennia, have fault planes exposed along the bedrock scarps juxtaposing the pre-Quaternary bedrock against Quaternary slope deposits (Cello et al., 1997; Galadini and Galli, 2000, 2003) or clearly affect and displace fluvioglacial alluvial fans or alluvial terraces

along the mountain slopes (Galadini and Galli, 2000, 2003) and lacustrine deposits within basins (Galadini and Galli, 1999).
The major tectonic structures observed in the affected area are the active faults along the western slopes of the Laga Mts. and the Mt. Vettore as well as the Norcia fault system.

2.2.1. Laga Mts. Fault

The Laga Mts. fault is a 30 km-long, NW-SE striking and SW-dipping active normal fault bounding the western slope of the arenaceous Gorzano Mt. reaching altitudes of 2458 m a.s.l. as a part of the Laga chain (Calamita and Pizzi, 1994; Cello et al., 1997; 1998; Galadini and Galli, 2000, 2003; Galadini and Messina, 2001). It dislocates an Early Pliocene anticline structure consisting of Middle-Late Miocene marls (Cerrogna Marls and Pteropodi Marls formations) overlaid by early Messinian siliciclastic turbidites (Laga formation) (Centamore et al., 1991; Marsili and Tozzi, 1991; Calamita et al., 1995; Ghisetti and Vezzani, 2000). Two mountainous intermontane basins occur in its hangingwall: the Amatrice and Campotosto basin along the northern and southern part of the fault respectively. These basins are filled with continental deposits (Demangeot, 1965; Bachetti et al., 1990; Blumetti et al., 1993; Cacciuni et al., 1995).
The Amatrice basin is composed of Early Pleistocene glacis deposits, overlaid by large landslide bodies, and by terraced fluvial deposits presumably of Middle and Late Pleistocene age (Blumetti et al., 1993), while the Campotosto basin comprises coalescent alluvial fans and heteropic swamp deposits radiocarbon dated to 39700 ± 3000 years BP with lack of old Quaternary continental deposits (Bachetti et al., 1990) indicating that it nucleated quite recently and that it is younger than the Amatrice basin (Galadini and Messina, 2001).
As far as the Quaternary activity is concerned, Galadini and Messina (2001) suggested the segmentation of the Laga Mts. fault taking into account the occurrence of two distinct mountainous intermontane basins in the hangingwall of Laga Mts into two distinct structures: the northern segment of pre-Late Quaternary activity constituting the eastern boundary of the mountainous inter-montane Amatrice basin and the southern segment of Late Quaternary activity bounding the mountainous intermontane Campotosto basin to the east. They also support an along-strike migration of the fault activity without any conclusive explanation for this migration process. However, Boncio et al. (2004) supported that there are neither significant geometrical nor structural complexities available for the justification of fault segmentation. Moreover, the analysis of the fault displacement does not support the hypothesis of segmentation.
Unlike most of the other structures surrounding the affected area, this fault affects the Miocene clayey-arenaceous bedrock of the Laga Mts., a lithology on which fault scarps related to recent fault activity are rarely formed and retained for a long period of time. However, the fault plane is well exposed in its central part where it dislocates Cerrogna Marls formation with N140-150° strike, 60-70° dip to the SW, N220-230° average slip vector and kinematic indicators including calcite shear fibres, abrasion striae, grooves and foliated cataclasite as well as in its northern part and more specifically north of Amatrice with N 155-165° strike and 80-85° dip to the SW (Calamita and Fizzi, 1992, and references therein; Cello et al., 1997; Boncio et al., 2004). The preservation of the fault scarp in its central part is due to the occurrence of massive to thick layered arenaceous beds of the basal Laga formation in the footwall block displaced against less cohesive alternations of pelites and arenites of the upper Laga formation (Boncio et al., 2004).
Furthermore, impressive geomorphological evidences of recent activity include slightly degraded but well-defined triangular facets developed along this mountain front and fault scarps affecting alluvial, colluvial and slope deposits (Blumeti et al., 1993; Cello et al., 1997, 1998; Galadini and Messina, 2001). At its northern termination, the fault progressively disappears, while in its southern termination it is clearly intersected by an E-W-striking and S-dipping normal fault of the Gran Sasso normal fault system (Boncio et al., 2004).
Based on paleoseismological analysis including excavation of trenches, radiocarbon dating and mineralogical analysis, Galadini and Gilli (2003) identified two events along the Laga Mts. fault, both occurred after 8320-8150 years BP, estimated a paleoseismologically inferred minimum slip rate of 0.12 mm/yr, a geomorphologically inferred vertical slip rate (based on the displacement of Late Pleistocene landforms) of 0.7-0.9 mm/yr, the recurrence interval not longer than 7570 years, a

minimum elapsed time fixed in eight centuries and the maximum expected magnitude equal to M 6.6.

2.2.2. Mt. Vettore Fault

The Mt. Vettore fault is located in the high mountainous environment of Sibillini chain reaching altitudes of about 2500 m.a.s.l., northeast of the Laga Mts. It comprises NNW-SSE to NW-SE striking branches with a total length of 18 km (Calamita et al., 1992; Cello et al., 1997; Galadini and Galli et al., 2000, 2003). It is made of at least three parallel splays with the southern sector of the fault hosting significant evidence of recent tectonic activity comprising fault scarps along the western slope and the piedmont area of the Mt. Vettore (Galadini and Galli et al., 2000, 2003). More specifically, the main scarp affects the upper part of the western slope of the Mt. Vettore and displaces the carbonate bedrock, while another scarp occurred in the middle of the western slope and juxtaposes the carbonate bedrock against the Late Pleistocene slope deposits (Calamita and Pizzi, 1992; Coltorti and Farabollini, 1995; Galadini and Galli et al., 2000, 2003). A third fault scarp (Prate Pala scarp) is located along the piedmont area and affects a Late Pleistocene - Holocene alluvial fan of Castellucio plain (Galadini and Galli et al., 2003).
The Castellucio intermontane basin is a tectonic depression formed in the hangingwall of Mt. Vettore fault and is filled with Late Quaternary fluvial and fluvio-lacustrine sediments (Cello et al., 1997). The deposition in the piedmont area is comprised by clastic and landslide material produced by the Mt. Vet-tore western slope and alluvial deposits in the piedmont area (Coltorti and Farabollini, 1995). A large alluvial fan fed by creeks is composed of sediments indicating five different depositional phases with the first phase related to the Last Glacial Maximum (about 22.600 years BP in the Central Apennines), the forth phase related to the boundary Late Pleistocene-Holocene and the fifth phase related to about 3800-3200 years BP, while there are no chronological constraints available for the second and the third alluvial phases (Galadini and Galli et al., 2003).
Based on paleoseismological analysis including excavation of trenches, radiocarbon dating and mineralogical analysis, Galadini and Gilli (2003) identified three events along the Mt. Vettore Fault occurring between 4155-3965 years BP and the 6th-7th century A.D. (E1), between 5940-5890/5795-5780 years BP and 4155-3965 years BP (E2), and between 18000-12000 years BP and 5940-5890/5795-5780 years BP (E3) respectively, minimum vertical slip rates of 0.11-0.36 mm/yr (paleo-seismologically inferred) and 0.36-0.62 mm/yr (geomorphologically inferred), a recurrence interval not longer than 4690 years, a minimum elapsed time of 1300-1500 years since the last Mt. Vettore fault activation and the maximum expected magnitude equal to M 6.5.

2.2.3. Norcia Fault System

The 27-km-long Norcia fault zone is located west of the Mt. Vettore fault and is composed of several NNW-SSE striking fault branches (Preci, Campi, Norcia, Ocricchio, Mt. Alvagnano faults) constituting the eastern mar-gin of the Norcia basin, which is a tectonic depression filled with Pleistocene-Holocene fluvio-lacustrine sediments (Cello et al., 1997, 1998; Galadini and Galli, 2000; Boncio et al., 2004). Evidences of recent activity are observed along the Norcia fault system. Bedrock fault scarps are observed along the Mt. Alvagnano fault resulting in surface faulting during the 1979 Norcia earthquake (Blumetti, 1995; Camassi and Stucchi, 1997) and the Norcia fault displaces the Late Pleistocene slope deposits (Blumetti, 1995), while the Preci, Campi and Ocricchio faults are not characterized by either geologi-cal or geomorphological evidence of recent activity (Galadini et al., 1999). Based on the vertical offset affecting a dated alluvial fan along the Norcia fault, Blumetti (1995) calculated a minimum slip rate of 0.2 mm/yr. Galadini and Galli (2000) referred to a chronological interval of 0.1 Ma years and an elapsed time of 313 years since the last earth-quake. Instrumental data by Deschamps et al. (1979) along with small surface ruptures indi-cate that the Norcia fault is the causative fault of the 1979 Norcia earthquake and it could be one of the causative faults of the January 14, 1703 earthquake (Blumetti, 1995; Cello et al., 1998; Galadini and Galli, 2000, Galli et al., 2005).

3. HISTORICAL RECORD AND SEISMIC HAZARD OF THE AFFECTED AREA

The activity of the CAFS is characterized by moderate earthquakes and a few major historical events within the Umbria-Abruzzi Apennines with magnitudes of 6.5-7.0 and maximum intensities of X-XI$_{MCS}$ (Cello et al., 1998. and references therein). As far as the 2016 affected area is concerned, the 1639 Amatrice earthquake (Mw=6.3, I=X), the 1703 Norcia earthquake (Mw=6.8, I=XI) and the 1979 Norcia earthquake (Mw=5.9, I=VIII-IX) are the most significant events for the characterization of this area as a seismogenic zone. The affected area has been also struck by a number of small-to-moderate events since 1000 A.D. (I≤VIII) including the events of July 1627 (M=5.1, I=VII-VIII), November 1883 (M=4.8, I=VII), February 1906 (M=4.3, I=VI), December 1910 (M=4.8, I=VII), March 1950 (M=4.8, I=VII) and July 1963 (M=4.3, I=VI) (Gruppo di Lavoro CPTI, 1999; Boncio et al., 2004) and also by three minor earthquake sequences during the 1990s (August 1992, M=3.9; June 1994, M=3.7 and October 1996, M=4.0; De Luca et al., 2000), which may be interpreted as seismic dislocations on minor structures accommodating volumetric deformation at the lateral tip of the Laga Mts. fault plane (Boncio et al., 2004).

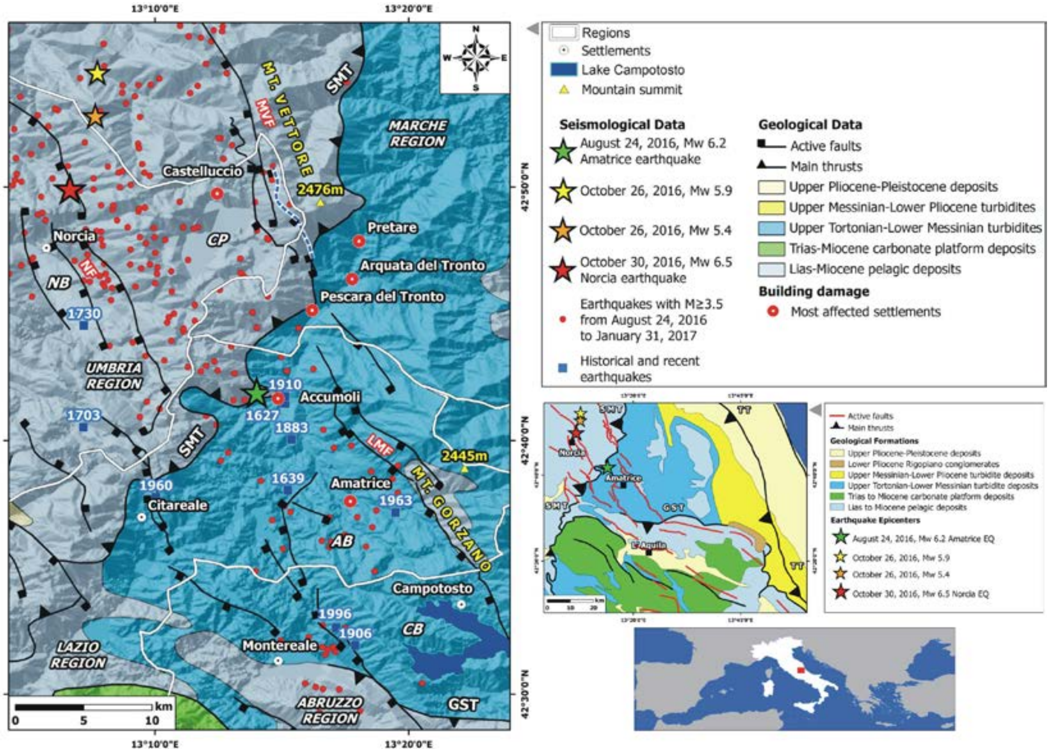

Figure 1. Geological maps of the Umbria-Marche Apennines (Central Italy) affected by the 2016 Central Italy earthquakes comprising the August 24, Mw 6.2 Amatrice earthquake, the October 26, Mw 5.9 and 5.4 events and the October 30, Mw 6.5 Norcia earthquake. The most imprortant historical and recent events are also presented. AB: Amatrice Basin, CB: Campotosto Basin, CP: Castellucio Plain, NB: Norcia Basin, GST: Gran Sasso thrust, SMT: Sibillini Mts thrust, TT: Teramo thrust.

4. TYPE OF BUILDINGS IN THE AFFECTED AREA AND SEISMIC CODES

The dominant types of structures in the affected area are (i) reinforced concrete (R/C) and (ii) unreinforced masonry (URM) buildings including monumental structures.

The mainly two- to four-storey R/C buildings are structures comprising generally an R/C frame and infill walls and are classified into two categories: (a) non-ductile R/C buildings with normal strength concrete dated back to the post-WWII period and now at the end of their conventional life cycle with probable decay problems affecting the mechanical properties of their elements and (b) recent R/C buildings constructed according to recent antiseismic specifications during the last decades.

Traditional URM buildings comprise the majority of the building environment in the affected area and date back as far as medieval times. They have a load-bearing system which includes masonry load-bearing walls constructed mainly with materials such as stones and bricks laid in parallel horizontal courses and often jointed using mortars of poor and inadequate quality. These walls are disposed orthogonally to each other in order to succeed a three-dimensional box behavior. Curved elements such as arches and barrel or cross vaults sustain the horizontal floors. Windows and doors are regularly placed on the external walls of the building.

As far as the reinforcement is concerned, the original reinforcements of URM buildings include wooden bars embedded in the masonry, while strengthening interventions especially after strong earthquakes include transversal iron tie rods, ring beams at the floor levels and R/C slabs replacing vaulted structures (Ceci et al., 2010).

The use of sub-par materials in URM buildings is partially assigned to the recurrent destructive earthquakes causing partial collapse and subsequent reconstruction of several historical buildings. The rapid post-earthquake reconstruction sometimes encouraged in the past centuries the use of less skilled construction workers and builders resulting in poor workmanship and the recycling of inadequate materials from collapsed buildings. This is confirmed by frequent observations of dis-homogeneous portions in the masonry walls of the buildings affected by the 2016 Central Italy earthquakes, in which the typical irregular stonework is mixed with pebbles and clay brick fragments.

Despite this variety of structures and their differences, one thing they all have in common is the fact that they are non-engineered and are not earthquake resistant. This is attributed to the fact that they have been constructed in a time period during which the earthquake-resistant construction as well as the repair and retrofitting of structures did not exist as a way of prevention and mitigation against the destructive earthquake effects on buildings as the first rudimentary rules for seismic structural design were drawn during 18th century after the 1783 Messina, 1857 Ancona and 1859 Norcia earthquakes. The current Italian seismic code and the related seismic hazard maps were introduced in 2008. According to these maps, the peak ground acceleration (PGA) for a 10% probability of exceedance in 50 years (475 years return period) for the affected area ranges from 0.400 to 0.450g.

Based on the aforementioned paleoseismological results and the historical and modern seismicity, it is also significant to note that the recurrence interval of destructive earthquakes is much larger from the average life span of a generation. If such an event took place during a generation, then construction workers and builders had the opportunity to learn from their mistakes and the ability to transfer the knowledge and cumulative lessons to successor workers. If such an event took place after a few generations passed, then the collective memory of construction workers and builders is either composed more of historical events than of actual memories or totally erased. This fact results in increased primary seismic vulnerability of buildings in the affected area, due to the fact that those dealing with the building construction did not have the opportunity to improve their construction methods as well as materials and technology for the aforementioned reasons.

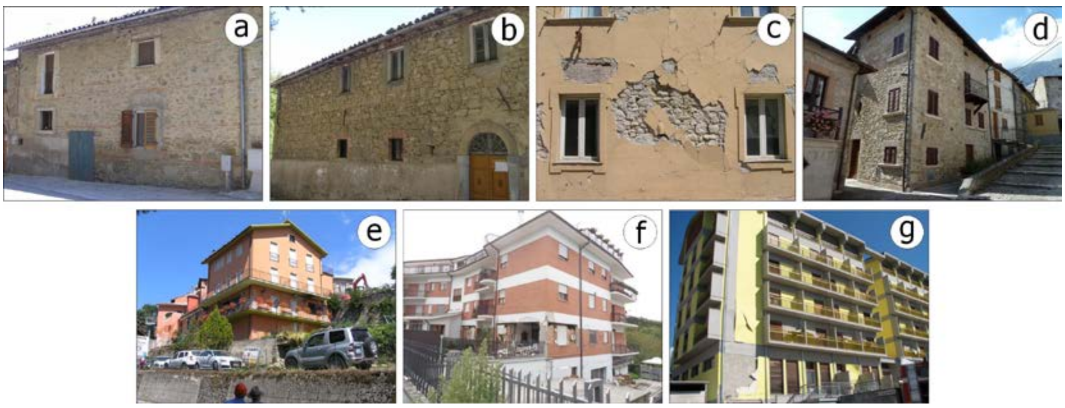

Figure 2: Dominant building types in the area affected by the August 24, 2016 Mw 6.2 Amatrice and the October 30, 2016 Mw 6.5 Norcia earthquakes. The majority of buildings are masonry structures dated back to the medieval times with high seismic vulnerability (a-d). Many buildings in Norcia town and few in other settlements of the affected area have been reinforced (b and d) after the 1979 Norcia and 1997 Umbria and Marche earthquakes. (e-f) Non-ductile R/C buildings with normal strength concrete dated back to the post-WWII period and now at the end of their conventional life cycle with probable decay problems affecting the mechanical properties of their elements. (g) Recent R/C buildings constructed during the last decades according to modern antiseismic specifications.

5. DAMAGE TO BUILDINGS INDUCED BY THE 2016 CENTRAL ITALY EARTHQUAKES

The R/C buildings suffered non-structural damage by the 2016 Amatrice earthquake including horizontal cracking of infill and internal partition walls, detachment of infill walls from the surrounding R/C frame and of large pieces of plaster from walls. As regards the structural damage, it varied from light damage in R/C elements to partial or total collapse of the building. More specifically, it comprised light cracks in columns, soft story failure due to absence of infill walls, symmetrical buckling of rods, compression damage at midheight of columns and bursting of over-stressed columns resulting in partial or total collapse. Strong evidences of the effect of the vertical ground motion in RC buildings are the symmetrical buckling of reinforcement, the compression damage and crushing at midheight and in other parts of columns, the undamaged windows and the unbroken glass panels as well as the partial collapse of the buildings that usually occur along the vertical axis within the plan of the building.
Damage to RC buildings are attributed to (a) the poor quality of concrete with compressional strength lower than the expected and inadequate reinforcement, (b) the absence of earthquake resistant features even in recent constructions, (c) the inappropriate foundation close to the edge of the slopes of flat hills that also leads to differential settlements creating cracks homologous to those seismically induced and (d) the destructive effect of the vertical component of the earthquake ground motion.
The URM buildings suffered non-structural and structural damage varying from cracks and detachment of large pieces of plaster from walls to mainly and mostly destruction of the building. Moreover, damage to masonry walls, piers, floors and roofs was also observed.
Damage to URM buildings are attributed to (a) the poor workmanship with randomly placed materials of poor and inadequate quality bound by low-strength mortars and without any antiseismic precautions, (b) the effect of the vertical component of ground motion to buildings as well as (c) the inadequate interventions and modifications after previous earthquake damage.

Figure 3. Damage induced by the August 24, 2016 Mw 6.2 Amatrice earthquake. (a) Partial collapse of the masonry load-bearing walls in Amatrice area after the August 24 Mw 6.2 main shock. (b) The same building after an Mw 4.3 aftershock on August 25. (c-d) Cracking, detachment of pieces of plaster from the masonry and partial collapse of masonry in unreinforced masonry building in Accumoli. The buildings presented in 3a-3d razed to the ground after the earthquakes of October 2016. (e-h) Non-structural damage observed in an R/C building in Amatrice comprised cracking of the external infill walls and detachment of the infill walls from the surrounding R/C frame.

The October 30, 2016 Mw 6.5 Norcia (Italy) earthquake had a significant impact on Norcia town and the surrounding area. Due to the small epicentral distance, Norcia suffered extremely high accelerations with a value of horizontal PGA of 0.48 g registered at the nearest seismic station (Luzi, 2016).
Masonry residential buildings in Norcia town and its surrounding area comprising Visso, Ussita, San Pellegrino, San Severino Marche, Casavecchia alta, Pieve Torina and Fontevena settlements suffered not only non-structural but also structural damage. The first included cracks in the masonry walls, detachment of plaster pieces from the masonry walls and of tiles from roofs as well as fall of loose stones from upper parts of the buildings. Structural damage included partial collapse of masonry walls

and total destruction of the structure. Similar structural damage was also sustained by monumental structures (churches) in Norcia town with the almost total collapse of the San Benedetto basilica being the most characteristic example of church destruction.

As regards the seismic response of R/C buildings during Norcia earthquake, several damage occurred to non-structural elements and especially to infill and partition walls comprising cracking of the infill walls, detachment of plasters from the walls as well as detachment and ejection of the infill walls from the surrounding R/C frame. Structural damage in R/C buildings comprised soft storey failure especially after the detachment and ejection of the infill wall from the surrounding R/C frame resulting in abrupt variation of stiffness. Failures of columns were also observed and included degradation of column top, concrete disorganization, flexural cracks as well as buckling of longitudinal and transversal rods of the columns on the verge of collapse due to inadequate reinforcement. Beam-column joints were also detected and attributed to the large forces during the severe ground shaking.

As far as the damage induced in Norcia town is concerned, its buildings were not severely affected by the Amatrice earthquake resulting in no damage at all or negligible non-structural damage to few of them. In contrast, buildings in settlements of Amatrice basin including Amatrice, Accumoli, Arcuata del Tronto and Pescara del Tronto suffered moderate to very heavy structural damage. Hence, the damage state of buildings after the Amatrice earthquake was DS0 for Norcia enabling buildings to withstand the subsequent earthquakes, while the damage state of buildings in Amatrice was much higher (≥ DS3) making them more vulnerable during the upcoming events of October 2016. As a verification of the aforementioned, the damage state in Amatrice basin after the Norcia earthquake dramatically increased from DS3 to DS5 (near total or total collapse) for the majority of the still standing buildings resulting in entire settlements razed to the ground. However, many historical churches in Norcia experienced the same damage state evolution characterized by damage increase.

The most important fact related to the Norcia earthquake is the zero human losses, which is a considerable achievement in comparison to the almost 300 victims caused by the Amatrice earthquake. Since the two seismic events were comparable and the small differences in the characteristics and the parameters of the earthquake ground motion are not enough for the interpretation, this significant difference is attributed not only to the large scale evacuation in the affected area that carried out by the Italian authorities after the earthquakes generated on October 26, 2016 for the evaluation of the structural stability of buildings in the affected area, but mainly to the satisfactory performance of buildings in Norcia attributed to an extensive retrofitting project of buildings followed the 1979 Norcia and the 1997 Umbria and Marche earthquakes.

The strengthening techniques used in Norcia comprised (a) confinement of masonry walls by a layer of mortar with a pre-fabricated steel welded mesh inside, in both faces, connected by steel bars at a given spacing and (b) introduction of steel cables connecting parallel walls in order to minimize the out-of-plane movement of exterior walls to the outside of the construction (Lopes et al., 2017). These construction details allowed the masonry walls to exhibit an in-plane behavior and to increase their resistance.

The vertical ground motion of these moderate shallow near-field normal-faulting earthquakes had very short duration and comprised high-frequency oscillations with small amplitudes as well as few low-frequency pulses with higher amplitudes. In contrast to the horizontal component of the ground motion, the seismic response of structures is not correlated with its conventional dynamic characteristics. Thus, conventional flexible or rigid structures in the affected area were equally damaged.

The high frequency of the vertical ground motion caused disintegration of the binding mortar of the load-bearing walls of the historical buildings of the earthquake-stricken area resulting in increasing of the already existing vulnerability. The observed building damage was due to impact-type phenomena produced on the buildings' foundations and in other parts leading to the failure of the structure. Collapses occurred rapidly and instantaneously as if explosives had been detonated in the building's foundation resulting in no time for residents to react. The buildings collapsed into their own footprint.

Partial collapse of buildings was also observed in the affected area. The remaining walls and columns (where existed) were vertical, the classical diagonal cracks were absent, while windows and glass panels remained intact. Picture frames, doors, radiators and other appliances were dismantled and fell down.

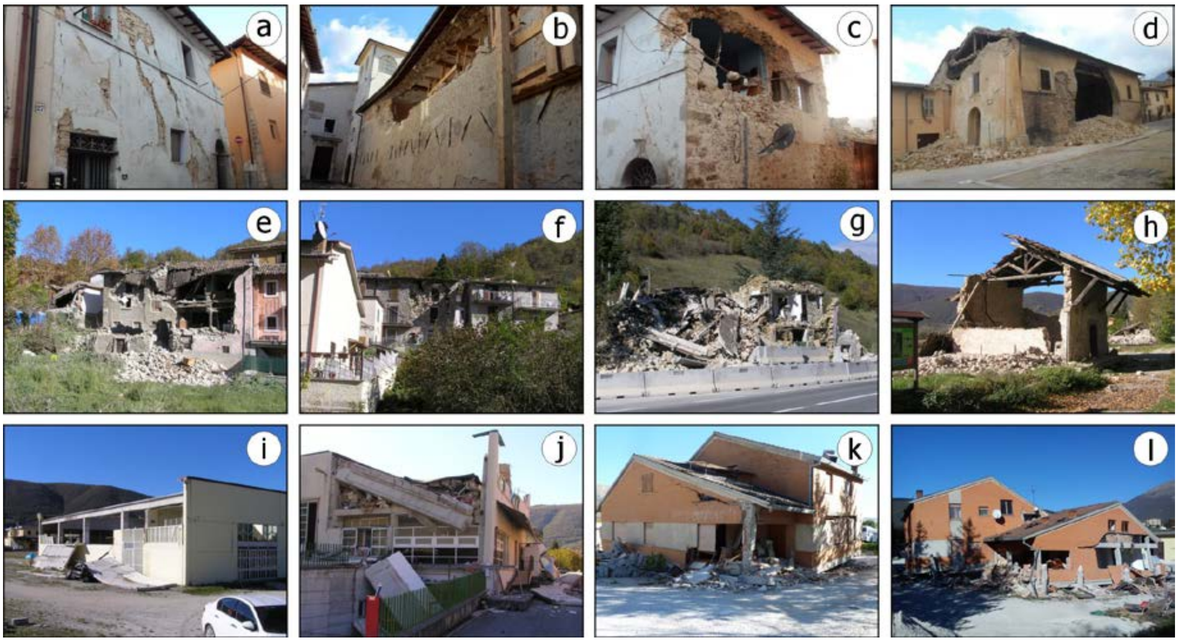

Figure 4. Representative view of the damage induced by the October 30, 2016 Mw 6.5 Norcia earthquake. (a) Cracking and detachment of plaster pieces from the masonry load-bearing walls of a masonry building in Norcia. (b) The wall failure in this masonry building was concentrated at a level higher to that of the seismic retrofit. (c, d) Failure of masonry load-bearing walls in masonry buildings in Norcia town. (e-h) Masonry buildings in damage state DS4-DS5 in Amatrice basin. The Nocria earthquake aggravated damage induced by the Amatrice earthquake and the seismic events of October 26. (i-l) R/C buildings in the industrial zone of Norcia suffered non-structural (i) and structural damage (j-l).

When the vertical component of the ground motion was acting, standing waves were formed vertically in the observed structures resulting in the collapse of one or more floors at any level of the building. At the same time, the overlying or underlying adjacent floors were completely horizontal and the corresponding parts of the building remained almost intact as if the partial collapse had not taken place. The same mechanism is responsible for the upward movement and dislocation of the highest parts of buildings, monuments and bell towers such as roof tiles, entire roofs, top of arcs etc.

Moreover, considerable damage including collapse of walls upon which floors may be laid was observed due to the vertical oscillation of the horizontal building body (wood or metal floors and roofs) in combination with the abovementioned standing waves.

As regards the effect of the vertical component of the earthquake ground motion during both earthquakes, the following damage is attributed to its destructive effect: (a) symmetrical buckling of longitudinal bars, (b) loosening of stirrups in ground floor columns, (c) compression damage at midheight of columns, (d) bursting of over-stressed columns, (e) collapse of walls away from URM and R/C buildings as by an explosion from within, (f) symmetrical distribution of damage around a vertical axis, (g) spatial homothetic motions in URM and RC buildings and (h) intact windows and unbroken glass panels. This damage indicates the prevalence of the vertical component of the earthquake ground motion over horizontal movements based solely on field macroseismic observations.

During on-site inspection in the affected area immediately after the earthquake, the authors had the opportunity to observe the damage induced not only by the main shock but also by its largest aftershocks generated during the first three days of the aftershock sequence. Bearing in mind that:

i. the soil conditions in foundations of the affected villages were neither changed nor altered,
ii. the conventional dynamic parameters of buildings did not play a significant role in their seismic response against the vertical component of the earthquake ground motion, due to its impact type of loading,
iii. the structures and materials have carried memories from the previous large shocks of this sequence and
iv. the main shock and its largest aftershocks caused damage on buildings including spatial homothetic motions,

it is concluded that:

i. the main shock and its largest aftershocks had similar focal mechanism parameters (normal faulting),
ii. the main shock and its largest aftershocks were shallow near-field seismic events with short duration but high amplitude,
iii. the observed damage is typical of such earthquakes and
iv. the vertical component of the earthquakes' ground motion has prevailed.

These homothetic motions were not an isolated case, but they reached statistically significant levels. Similar conclusions were drawn by Benedetti and Carydis (1999), Di Sarno et al. (2011), Carydis et al. (2012) and references therein after studying building damage induced by similar earthquakes generated in the Mediterranean region [1995 Aegion (Greece), 1995 Dinar (Turkey), 1999 Athens (Greece), 2009 L' Aquila (Italy) and 2012 Emilia Romagna (Italy) earthquakes].

Figure 5. (a) An R/C building in Amatrice suffered partial collapse after the Amatrice earthquake. Its remaining still-standing parts were practically undamaged. (b) The damage observed in the above mentioned R/C building was aggravated by an Mw 4.8 aftershock generated the day following the main shock. Spatial homothetic motions indicated the prevalence of the vertical component of the earthquake ground motion.

6. CONCLUSIONS

Both earthquakes induced non-structural and structural damage in the majority of buildings of the affected areas. In general, the Norcia earthquake aggravated damage induced by the Amatrice earthquake and the other two events generated on October 26 resulting in entire settlements razed to the ground.

The R/C buildings suffered non-structural damage including horizontal cracking of infill and internal partition walls, detachment of infill walls from the surrounding R/C frame and of large pieces of plaster from walls. As regards the structural damage, it comprised light cracks in columns, soft story failure due to absence of infill walls, symmetrical buckling of rods, compression damage at midheight of columns and bursting of over-stressed columns resulting in partial or total collapse. Strong evidences of the effect of the vertical ground motion in RC buildings are the symmetrical buckling of reinforcement, the compression damage and crushing at midheight and in other parts of columns, the undamaged windows and the unbroken glass panels as well as the partial collapse of the buildings that usually occur along the vertical axis within the plan of the building.

Damage to R/C buildings are attributed to (a) the poor quality of concrete with compressional strength lower than the expected and inadequate reinforcement, (b) the absence of earthquake resistant features even in recent constructions, (c) the inappropriate foundation close to the edge of the slopes of flat hills that also leads to differential settlements creating cracks homologous to those seismically induced and (d) the destructive effect of the vertical component of the earthquake ground motion. As a rule, the R/C buildings in the affected area presented better seismic response compared to masonry buildings.

The URM buildings suffered non-structural and structural damage varying from cracks and detachment of large pieces of plaster from walls to mainly and mostly destruction of the building. The reinforced masonry buildings of the affected area presented satisfactory seismic performance. Hence, there is an imperative need for an immediate retrofit of similar structures located in areas characterized by similar comparable seismic potential.

Damage to URM buildings are attributed to (a) the poor workmanship with randomly placed materials of poor and inadequate quality bound by low-strength mortars and without any antiseismic precautions, (b) the effect of the vertical component of ground motion to buildings as well as (c) the inadequate interventions and modifications after previous earthquake damage.

From the comparison between damage induced by the 2016 Amatrice and Norcia earthquakes, it is concluded that the lower levels of damage in Norcia town are mainly attributed to the retrofitting of buildings after the 1979 Norcia and the 1997 Umbria and Marche earthquakes. In contrast, several additions of new floors and new buildings attached to old ones were made over the years in Amatrice without strengthening and retrofitting against earthquakes.

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