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TITLE:

SEISMIC BEHAVIOUR OF ORDINARY MASONRY BUILDINGS DURING THE 2016 CENTRAL ITALY EARTHQUAKES

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ABSTRACT

Between August 2016 and January 2017 nine shallow earthquakes ranging from 5.0 and 6.5 of moment magnitude affected Central Italy, involving several municipalities wherein unreinforced masonry buildings are more than three quarters of all constructions. Damage state has been very severe, with sixteen settlements belonging to the municipalities of Amatrice, Arquata del Tronto, Accumoli. Castelsantangelo sul Nera and Norcia experiencing a cumulative European macroseismic scale intensity larger than IX. Ground motion demand in terms of peak ground velocity was approximately two or three times what expected for a 475 years return period while the pseudo-acceleration spectra showed values between once and twice gravity acceleration for the period range typical of two and three storeys unreinforced masonry buildings. Moreover, since October 2016, such large seismic demand acted on structures damaged from previous shocks testifying the effects of damage accumulation, too. The significant shaking alone cannot explain the extremely severe damage of some settlements, with large portions of whole blocks completely collapsed, highlighting the need for investigating the specific vulnerability factors and construction features of unreinforced masonry buildings in the affected area. In fact, although some deficiencies already highlighted in previous Italian earthquakes (e.g. inadequate structural connections) have been surveyed also during this sequence, a marked vulnerability of masonry and its mortar has been noticed, in particular in the area between Amatrice and Arquata del Tronto. On the contrary, the historical constructions in Norcia performed much better, as a result of the 1860 seismic code and of the retrofitting interventions implemented after the different earthquakes occurred in the last two centuries. Finally, a number of demolished and rebuilt constructions performed very well, and this was also the case also of modern hollow clay blockwork buildings that protected not only human life, but also cost of construction and continuity of use.

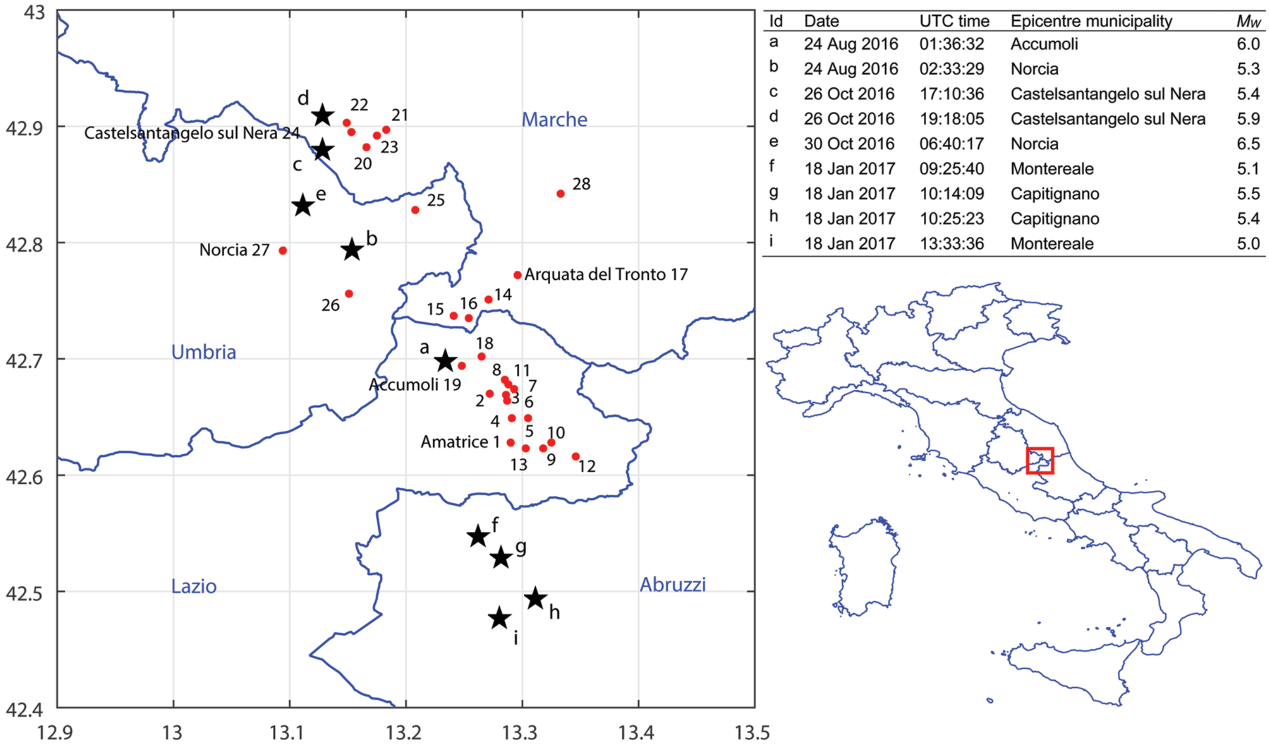
KEYWORDS

Amatrice; Damage accumulation; Historical masonry; Historical seismicity; Modern masonry; Mortar quality; Norcia

1 INTRODUCTION

On the 24th August 2016, at 1.36 Coordinated Universal Time (UTC), 3.36 local time (http://cnt.rm.ingv.it), a seismic sequence started in Central Italy with a moment magnitude M_W 6.0 earthquake with epicentre located within the municipality of Accumoli (Fig. 1). The seismic sequence continued with a M_W 5.3 event the same day at 2.33 UTC (epicentre close to Norcia), two events on the 26th October (M_W 5.4 and M_W 5.9, epicentres close to Castelsantangelo sul Nera, s/N) and a substantial M_W 6.5 on the 30th of October (epicentre close to Norcia), the largest earthquake in Italy since 1980. Four significant shocks with $5.0 \leq M_W \leq 5.5$ occurred on the 18th of January 2017 (epicentres close to Capitignano). The sequence caused extensive damage in an area of Central Italy belonging to four different regions: Lazio, Umbria, Marche and Abruzzi (Fig. 1).

After the 24th August event a first systematic field survey was carried out. It led to the attribution of the intensities according to the European Macroseismic Scale (EMS, Grünthal 1998) reported in Table 1 for the most affected settlements and some other locations mentioned hereinafter. Three localities, the historical centres of the municipality of Amatrice, Saletta (belonging to the same municipality) and Pescara del Tronto (d/T) suffered a EMS intensity I_{EMS} = X, while another five I_{EMS} = IX-X. The severity of damage was worsened by the sequence, so that after the events at the end of October 2016 a cumulative I_{EMS} = XI was reached in Amatrice and Pescara d/T, X-XI in Illica and X in the settlements of Capodacqua, Tufo and Accumoli. The 2016-2017 sequence has been the most destructive in Italy since EMS intensities have come into use, because the maximum intensity in the 2012 Emilia seismic sequence has been VIII (Tertulliani et al. 2012), and in the 2009 L'Aquila Earthquake has been IX (Azzaro et al. 2011). As for Mercalli-Cancani-Sieberg (MCS, Sieberg 1930) intensities, the 2004 Molise Earthquake induced a IX-X (Galli and Molin 2004), the 1997-1998 Umbria-Marche sequence caused a maximum intensity of VIII-IX (Camassi et al. 2008), the 1980 Irpinia Earthquake several X and the 1976 Friuli sequence several IX-X (Rovida et al. 2016). According to Margottini et al. (1987), I_{EMS} = X roughly corresponds to I_{MCS} = XI.



Id	Date	UTC time	Epicentre municipality	M_W
a	24 Aug 2016	01:36:32	Accumoli	6.0
b	24 Aug 2016	02:33:29	Norcia	5.3
c	26 Oct 2016	17:10:36	Castelsantangelo sul Nera	5.4
d	26 Oct 2016	19:18:05	Castelsantangelo sul Nera	5.9
e	30 Oct 2016	06:40:17	Norcia	6.5
f	18 Jan 2017	09:25:40	Montereale	5.1
g	18 Jan 2017	10:14:09	Capitignano	5.5
h	18 Jan 2017	10:25:23	Capitignano	5.4
i	18 Jan 2017	13:33:36	Montereale	5.0

Fig. 1. Map of investigated area. Latin letters identify main earthquakes; Arab numbers identify settlements listed in Table 1.

Table 1. Observed EMS (European Macroseismic Scale) intensity after the 24th August (Azzaro et al. 2016), 26th and 30th October events (Tertulliani and Azzaro 2016), as well as PGV (Peak Ground Velocity), PGA (Peak Ground Acceleration) and $S_a | T = 0.3$ s (Spectral Pseudoacceleration at a period of vibration equal to 0.3 s) values for some of the settlements mentioned within the text. Values of PGV and PGA directly obtained from strong motion records are indicated in bold (Italian Accelerometric Archive, http://itaca.mi.ingv.it)

		I_{EMS}		PGV [cm/s]			PGA [g]			S_a(0.3 s) [g]		
Id	Settlement	24 Aug	30 Oct	24 Aug	26 Oct	30 Oct	24 Aug	26 Oct	30 Oct	24 Aug	26 Oct	30 Oct
1	Amatrice	X	XI	**44**	**5.4**	**38**	**0.87**	**0.09**	**0.53**	1.03	0.17	0.54
2	Saletta*	X		43	5.4	48	0.78	0.097	0.43	1.59	0.23	0.70
3	Casale*	IX-X		42	5	41	0.78	0.09	0.40	1.53	0.21	0.67
4	Petrana*	IX-X		40	4.5	38	0.75	0.08	0.40	1.39	0.19	0.62
5	Sant'Angelo*	IX-X		38	4.3	36	0.73	0.08	0.38	1.32	0.19	0.58
6	San Lorenzo a/F*	IX-X		41	5	40	0.77	0.09	0.40	1.47	0.21	0.65
7	Cossito*	VIII		43	5	43	0.77	0.09	0.41	1.54	0.21	0.71
8	San Tomasso*	VIII		43	5	46	0.77	0.10	0.43	1.56	0.21	0.78
9	Retrosi*	VIII	IX	27	3	21	0.53	0.06	0.32	0.90	0.14	0.48
10	Moletano*	VIII	VIII	27	4	31	0.53	0.07	0.35	0.90	0.18	0.43
11	San Capone*	VII-VIII		43	5	43	0.77	0.10	0.41	1.55	0.22	0.71
12	Preta*	VI-VII	VII-VIII	21	3	25	0.40	0.06	0.28	0.73	0.14	0.39
13	San Cipriano*	VII		30	3.8	30	0.58	0.07	0.35	1.00	0.16	0.45
14	Pescara d/T*	X	XI	38	11.7	75	0.43	0.18	0.50	0.82	0.27	1.03
15	Capodacqua*	VIII-IX	X	36	5.7	49	0.58	0.12	0.58	1.16	0.19	1.25
16	Tufo*	VIII-IX	X	37	6	46	0.63	0.13	0.56	1.26	0.20	1.16
17	Arquata d/T	VIII-IX	IX-X	18	6	34	0.25	0.13	0.45	0.45	0.17	0.76
18	Illica*	IX-X	X-XI	42	5.7	51	0.76	0.11	0.51	1.54	0.23	0.94
19	Accumoli	VIII	X	42	**4**	**40**	0.76	**0.09**	**0.56**	1.54	0.23	0.94
20	Gualdo*	VII	IX-X	15	26	40	0.23	0.46	0.47	0.43	0.96	1.06

21	Macchie*	NA	IX-X	17	37	45	0.23	0.44	0.44	0.37	1.01	0.87
22	Nocria*	NA	IX-X	17	27.6	38	0.29	0.46	0.46	0.49	1.02	0.93
23	Vallinfante*	NA	IX-X	17	34.5	43	0.24	0.45	0.45	0.40	1.01	0.90
24	Castelsantangelo s/N	VI	IX	16	**36.5**	**38**	0.26	**0.54**	**0.55**	0.45	1.03	0.91
25	Castelluccio*	VI-VII	IX-X	38	**12.8**	**66**	0.36	**0.22**	**0.80**	0.65	0.56	1.14
26	San Pellegrino*	VII-VIII	IX-X	53	11	58	0.38	0.198	0.55	0.76	0.26	1.30
27	Norcia	V-VI	VIII-IX	**30**	**21**	**56**	**0.37**	**0.21**	**0.49**	0.56	0.46	0.89
28	Montegallo	VI-VII	VII	10	8	17	0.14	0.15	0.28	0.26	0.21	0.36

*Casale, Cossito, Moletano, Petrana, Preta, Retrosi, Saletta, Sant'Angelo, San Capone, San Cipriano, San Lorenzo a Flaviano and San Tomasso belong to the municipality of Amatrice, Capodacqua, Pescara del Tronto and Tufo to Arquata del Tronto, Illica to Accumoli, Gualdo, Macchie and Vallinfante to Castelsantangelo sul Nera, Castelluccio and San Pellegrino to Norcia.

Instrumental intensity measures of the ground shaking are also reported in Table 1, such as PGA (Peak Ground Acceleration), pseudoacceleration response spectrum at a period of vibration equal to 0.3 s and PGV (Peak Ground Velocity), a parameter available for the affected area and better associated with the seismic response of masonry buildings compared to acceleration measures (Mouyiannou et al. 2014). For some of the affected settlements recorded values of PGV and PGA are available (bold numbers in Table 1, http://itaca.mi.ingv.it), whereas elsewhere existing shakemaps have been used (http://shakemap.rm.ingv.it/shake/7073641/pgv.html, http://shakemap.rm.ingv.it/shake/8863681/pgv.html). It is understood that shakemaps can provide only approximate estimation of experienced shaking, because ground motion attenuation curves are used in case of data gaps and because ground motion can vary greatly over small distances.

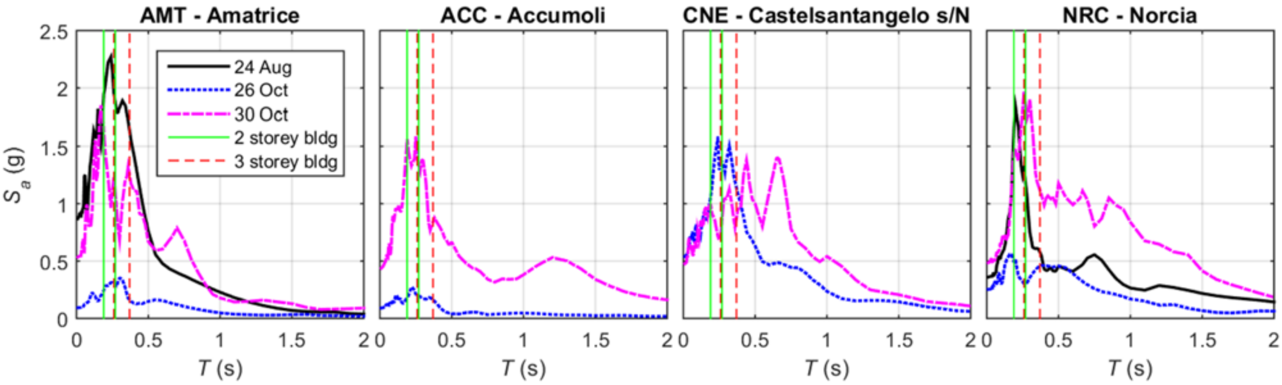


Fig. 2. Pseudoacceleration response spectra of E-W component representative of the three main shocks of 24th August (M_W 6.0), 26th October (M_W 5.9), 30th October (M_W 6.5) 2016.

For the 24th August event PGV values exceeding 40 cm/s were recorded and estimated in the municipality of Amatrice, whereas for the M_W 5.9 26th October event it reached a value higher than 35 cm/s only in Castelsantangelo s/N and for 30th October earthquake PGV exceeded 50 cm/s in Norcia, Castelsantangelo s/N and Arquata d/T. For the 2009 L'Aquila Earthquake recorded values in the historical centre have been in the range 34-39 cm/s (http://shakemap.rm.ingv.it/shake/1895389/pgv.html). PGV values can be compared with those expected based on hazard studies. Following Booth (2007), PGV has been obtained from peak pseudovelocity of a smoothed spectrum, which has been defined according to the Italian building code (DMI 2008). When no accelerometric station was present, site conditions have been estimated from the global model of velocity of shear waves in the top 30 m by Allen and Wald (2009), which delivers for the considered settlements velocities in the range 431-760 m/s, corresponding to ground type B according to the Italian code. Consequently, expected PGVs for a 475 return period event are equal to 14-27 cm/s (21-22 cm/s in nearly all most stricken settlements), much lower than what experienced in most of the places listed in Table 1.

The severity of the shaking is evident. Nonetheless, damage can vary substantially in the same settlement and from settlement to settlement (e.g., compare San Capone to Amatrice) despite PGV values similarity. Therefore, it arises the interest to investigate the building features.

To further describe the seismic sequence intensity, Fig. 2 shows the pseudoacceleration response spectra obtained from the East-West (most severe) component records of some stations located close to the most affected historical centres. In particular, data have been obtained from the ITACA database (http://itaca.mi.ingv.it) by selecting the following stations: AMT for Amatrice, ACC for Accumoli (where no accelerometric station was present at the time of the first shock), CNE for Castelsantangelo s/N (where records of the first event are not reliable), and NRC for Norcia. AMT and NRC stations are classified as ground type B, ACC as ground type A, CNE station as ground type C, respectively. Vertical lines in Fig. 2 aim at being representative of the expected fundamental periods of two and three storeys unreinforced masonry typical buildings, which the paper focus to, in elastic and cracked conditions, respectively. Fundamental periods in elastic phase have been assessed through the empirical expression adopted also in EC8-1 (2004) for unreinforced masonry buildings (which is 0.05 $H^{0.75}$ with H total height of the building, having assumed an interstorey height equal to 3 m); then, cracked periods follow by multiplying the elastic ones by $2^{0.5}$. It is evident how for most events low-medium rise unreinforced masonry buildings are in the maximum amplification region of response spectra and subjected to significant damage accumulation effects, as documented also in § 3. Additional information about 2016-2017 ground motion demand on structures are given by Mollaioli et al. (2017).

According to media sources (http://www.ilpost.it/2016/08/29/terremoto-amatrice-accumoli-arquata-tronto/), the 24th August event caused 229 deaths in the municipality of Amatrice, 50 in that of Arquata d/T and 11 in Accumoli. Slightly higher figures have been released in September, with 241 deceased in Accumoli and Amatrice (http://ilcentro.gelocal.it/laquila/cronaca/2016/09/12/news/terremoto-di-amatrice-l-elenco-ufficiale-delle-vittime-1.14090333), and 51 in Arquata d/T (http://www.prefettura.it/ascolipiceno/news/3306928.htm). Although no official statistics have been published, personal communications to the authors by public officials involved in the emergency management indicate that most of the victims perished in unreinforced masonry buildings. The larger vulnerability of historical unreinforced masonry buildings compared to reinforced concrete buildings seems consistent with recent Italian earthquakes, such as 1997 Umbria Marche (Spence and D'Ayala 1999), 2002 Molise (Decanini et al. 2004), 2009 L'Aquila (D'Ayala and Paganoni 2011) and 2012 Emilia (Penna et al. 2014). The performance of historical unreinforced masonry buildings will be discussed in this paper with reference to ordinary construction details, whereas the effectiveness of recent interventions, such as ring beams, repointing, injections, stitching of wall intersections, reinforced concrete coating, insertion of a steel moment resisting frame, is discussed by Sisti et al. (2017), and the performance of churches is investigated by Borri et al. (2017). An analysis of the performance of nonstructural elements in masonry constructions and monuments is presented in Perrone et al. (2017).

2 BUILDING FEATURES

2.1 *Stock of buildings and census data*

Considering the second-last census (ISTAT 2001), for which disaggregation for individual census zones within a municipality is available, the frequency of unreinforced masonry constructions in Accumoli, Amatrice, Arquata d/T, Castelsantangelo s/N, and Norcia is between 78 and 97% (Table 2), with usually slightly larger values in the main historical centre, whereas the national percentage is 61% (ISTAT 2011). As for the age of construction, an important threshold is a standard issued in the early 1960s (Zucconi et al. 2017). Indeed, percentages of buildings dating before 1962 vary between 47 and 89%, with an older stock in most main historical centres, whereas the Italian percentage is 46%. Lowest values are observed in Norcia that was able to attract significant touristic flows with the consequent construction activity. Vulnerability studies have shown that the number of stories is an important parameter for earthquake performance, with relevant differences for structures up to two stories and with three or more (Rota et al. 2008; Cattari et al. 2012). Buildings with up to two stories vary between 53 and 83% of the total, with national average (76%) falling within such range. However, the historical centre of Norcia has a much higher occurrence of low-rise buildings, a feature that will be explained in the following.

Therefore, although from the number of stories point of view there is no marked deviation from the country statistics, a building portfolio with a higher rate of unreinforced masonry buildings and older buildings compared to the national stock is present in the area most affected by the seismic sequence started in August 2016.

Table 2. Percentage of residential buildings with respect to unreinforced masonry (URM) structure, age, and number of storeys, as well as population total for most affected municipalities. In brackets data related to the historical centre of the main settlement of the municipality

	URM [%]	Age [%]	Storey [%]				Population	
		< 1962	1	2	3	> 3	1921	2011
Amatrice	94 (95)	74 (88)	12 (5)	53 (51)	34 (42)	1 (2)	10 043	2646
Arquata d/T	80 (90)	74 (98)	5 (3)	48 (42)	43 (37)	4 (18)	7227	1287
Accumoli	97 (98)	81 (91)	10 (1)	73 (73)	17(24)	1 (2)	2879	653
Castelsantangelo s/N	94 (87)	89 (82)	16 (21)	67 (55)	17 (23)	1 (2)	2012	310
Norcia	78 (95)	47 (82)	13 (16)	66 (74)	18 (11)	2 (0)	10 754	4915

These observations can be explained considering the population trend in these municipalities that shows a marked decrease. Compared to peaks occurred around 1921, 2011 population is about 15-26% in Castelsantangelo s/N, Arquata d/T, Accumoli, and Amatrice and 46% in Norcia (Table 2, last two columns). Therefore, it is expected a low maintenance level in several buildings, especially those in smaller settlements abandoned due to urbanisation, emigration, and demographic trends.

2.2 *Historical seismicity and construction standards*

The area affected by the earthquake has been subjected to earthquake-resistant construction standards at different stages. Amatrice was classified as seismic prone already in 1915 (RDL 1915), following the M_W 7.0 Marsica Earthquake of the same year. At that time there was just one seismic zone with a lateral coefficient equal to 0.10 g (Sorrentino 2007). Accumoli was the recipient of a similar provision in 1927 when two zones were defined, the second having a coefficient equal to 0.07 g (RDL 1927). Both Accumoli and Amatrice were included in the second zone. Norcia was included in the second zone in the early 1960s (L 1962), whereas Arquata d/T and Castelsantangelo s/N only about twenty years later (DM 1983), after a general revision of Italian seismic zonation following the 1980 Irpinia earthquake. Therefore, before earthquake resistant requirements were mandatory, about one quarter of Amatrice's, about one third of Accumoli's, about half of Norcia's and almost all of Arquata's and Castelsantangelo's constructions were built. Nonetheless, it is worth mentioning that explicit quantitative calculation of unreinforced masonry structures became mandatory only in the late 1980s for gravity and ordinary live loads (DMLP 1987), about ten years later for seismic loads (DMLP 1996), and only if design diverged from simplified rules. Otherwise, the seismic standard prescribed just geometry limitations, construction details and a minimum ratio between the area of structural walls and the total floor area in each direction.

Also relevant to describe the features of the buildings in the most affected area is the local historical seismicity. In Table 3, the local MCS macroseismic intensities of main historical earthquakes felt in most affected municipalities of the Central Italy 2016-2017 seismic sequence are reported. Only post 1600 events with local $I_{MCS} \geq$ VIII in at least one the municipalities of Amatrice, Arquata d/T, Accumoli, Castelsantangelo s/N and Norcia are considered. Observed intensities are listed by Locati et al. (2016) only for most severe events, whereas lower local felt intensities have been computed adopting the same procedure used in Sorrentino et al. (2014), and resorting to the epicentral intensities in Rovida et al. (2016). From Table 3 it is evident that Amatrice and Arquata d/T suffered the most damaging events in the 17th century and at the very beginning of the 18th century. The same applies partially also to Accumoli and Castelsantangelo s/N wherein, however, a I_{MCS} = VIII was observed in 1950 and 1859, respectively. On the contrary, Norcia has suffered from a much more intense and steadier seismic activity with seven events $I_{MCS} \geq$ VIII in the last four centuries. Among such events, the 1859 one is particularly significant, having caused 101 deaths over a population of 4500-5000 people (Boschi et al. 1998) and different degrees of damage in 749 buildings (Reale et al. 2004). Given the severity of the earthquake, the government of the Papal States, to which Norcia belonged at that time, sent a scientific mission led by the Jesuit and geodetic engineer Angelo Secchi (1860).

The surveyors noted damage concentration in buildings having more than two storeys above ground, thin and rubble masonry walls, heavy vaults without tie rods, hyp roofs without tie beams, whereas a tuff soil foundation improved the seismic response. Based on this inspection an innovative building code was released, with several provisions meant to improve the earthquake performance of the buildings (Reale et al. 2004).

Construction on sloping ground was discouraged and foundation should have been laid on a “solid and firm” soil below the superficial layer. Great attention was devoted to masonry construction. Mortar should have been manufactured with hydrated lime and sand washed with fresh water.

Table 3. Local MCS (Mercalli-Cancani-Sieberg) macroseismic intensity of main historical earthquakes.

	1639	1646	1703	1719	1730	1859	1879	1950	1979
Amatrice	IX	VIII	IX	V/VI	VII/VIII	VII	VI	VII	VI/VII
Arquata d/T	VIII/IX	< V	IX	VI	VII/VIII	VII/VIII	VI	VI/VII	VI
Accumoli	VIII/IX	VI/VII	X	VI	VII	VII	VI/VII	VIII	VII
Castelsantangelo s/N	VII/VIII	VII	IX/X	VII/VIII	VII	VIII	VI/VII	< V	VI/VII
Norcia	< V	IX	X	VIII	IX	VIII/IX	VIII	VI	VIII

Round stones were banned, and semi-dressed limestone units should have been used. Clay bricks were recommended for vaults. Walls had to be at least 0.6 m thick and have an additional tapered buttress having a 1/20 thickness-at-the-base/height ratio (Fig. 3a). Particular care had to be given to interlocking at wall intersections, openings had not to be too close to wall ends and had to be aligned vertically from one floor to the other.

The maximum height of constructions was limited to two storeys and 8.5 m at the eaves. These limitations applied also to damaged buildings to be repaired, so only undamaged or very lightly damaged third floors were preserved. As a matter of fact Norcia presents lower rise buildings (Fig. 3a-b) compared to other Italian historical centres and to the other municipalities most damaged by the 2016-2107 seismic sequence (Table 2). The girders of roofs and floors had to rest on the whole cross section of the walls, to which they had to be connected by metal anchors (Fig. 3a-b). Tie rods were compulsory when existing vaults were preserved at ground storeys. At the upper storey vaults were always forbidden and in the case of substantial repair works or new constructions they were permitted only in the basement. The minimum thickness of vaults was set to 250 mm or 1/18 of the radius, whichever the largest. Solid masonry had to connect wall and vault up to 1/3 of the rise. The recommendations in the building code were clearly inspired by the survey led by father Secchi, to which participated also architect Luigi Poletti, who performed several structural repair works after major earthquakes (Sorrentino et al. 2008).

Fig. 3. Norcia. Two-storey buildings, tapered wall thickness, systematic use of tie rods. a) via Cavour, b) piazza Giuseppe Verdi.

In 1979 Norcia has been hit by another earthquake, but damage was located in different portions of the historical centre compared to 1859 (Reale et al. 2004). This difference indicates that repaired buildings performed satisfactorily but also that the demolition of historical buildings to create the space for the new avenue, corso Sertorio, produced façades not connected adequately to pre-existing structures. The earthquake damaged 773 buildings, 55% of rubble stone masonry, 35% in dressed stone masonry or clay brick masonry, 10% of masonry buildings with ring beams. About 5% of the buildings suffered partial collapses, 32% heavy damage, 25% moderate damage and 38% slight damage (Favali et al. 1980). The combination of the 1859 building code and of a more recent seismic activity, with systematic strengthening (reinforced plaster was largely used), produced building characteristics in Norcia somewhat different from those in the other most affected municipalities, and these features contribute to explain the different performance (§ 3) (Sisti et al. 2017).

2.3 *Observed building features*

The municipalities of Arquata d/T and Norcia have been slightly involved by the 1997-1998 Umbria-Marche sequence. From the surveys performed at that time it is possible to gain additional information about their building features. Approximately three quarters (half) of buildings in Arquata d/T (Norcia) have unreinforced stone masonry structures and about one fifth (one third) of the floor diaphragms are rigid.

Fig. 4. Timber tie rods (blue frame) and steel wall anchors (red frame) in Castelsantangelo s/N: a) Via Parco della Rimembranza, b) via delle Mura Castellane.

Fig. 5. Mud mortar in: a) Accumoli, Illica, and b) Amatrice, Sant'Angelo.

Timber and/or steel tie rods are present also in Castelsangelo s/N (Fig. 4), although in a less systematic way than in Norcia. In Castelsantagelo buildings are mostly characterised by a rubble stone masonry with two leaves, not always well connected. The municipalities of Amatrice and Accumoli had been surveyed before the earthquake by Fumagalli et al. (2017). The historical centre of Amatrice had buildings clustered in structural aggregates, mostly two-three storeys high, with an average storey height in the 2.5-3.5 m range. Walls at ground floor had a mean thickness of about 0.70 m.

Fig. 6. a) I-beam and hollow clay block floor, Amatrice, Retrosi; b) Precast reinforced concrete beams and hollow clay block floor, Amatrice, Moletano.

Fig. 7. Iron wall anchor of timber tie, Amatrice, via Roma. a) General view; b) Close up of a wall anchor.

Fig. 8. Steel tie rods in the lightly coloured building. Amatrice, corso Umberto I. a) General view; b) Close up of a wall anchor.

The earthquake has shown how masonry had two or three unconnected layers across the thickness, units were not dressed and mortar was usually made of mud (Fig. 5). Intermediate horizontal structures were mostly timber structures and, to a lesser extent, jack-arch or I-beam and hollow clay block floors (Fig. 6). Structural vaults were present at ground floor in about one third of the building stock. Ties and/or ring beams were present in just about one fifth of the portfolio, much less than in Norcia (Fig. 3), either as iron wall anchors of timber elements (Fig. 7) or as modern steel rods (Fig. 8). The roof had a timber structure in most cases, but in about one tenth of cases it had been replaced by a reinforced concrete structure. In such instances internal horizontal structures had been usually replaced, as well.

Also in the historical centre of Accumoli buildings belong to structural aggregates, but they are mostly three storeys high. Walls were similar in technology but on average about 0.85 m thick. Floor diaphragms showed an higher occurrence of cast in place reinforced hollow clay block beams and precast reinforced concrete beams, as a consequence of the replacement of original elements. Similarly, the roof structure had been replaced in almost half the building stock. It is likely that the 1950 earthquake and, to a lesser extent, the 1979 one contributed to this higher occurrence of replaced horizontal structures (Sorrentino and Tocci 2008).

3 PERFORMANCE OF HISTORICAL BUILDINGS

The seismic sequence started on 24th August caused extensive damage, as shown from intensities reported in Table 1. Already after the first event usability inspections started and partial results have been published at mid October for some municipalities. Neglecting buildings unsafe to use due to an external hazard, such as a land-slide or a collapse-prone nearby structure, about 25% of the inspected buildings in Accumoli were usable, 12% temporarily or partially unusable, and 63% unusable. In Amatrice the same categories displayed the following values: 43%, 12%, 45%; while in Arquata d/T: 33%, 10%, 57%. Because, as shown in Table 2, most of the constructions are made of masonry it can be expected that previous quantitative values are representative of the performance of masonry structures.

Field surveys in the most affected area have shown catastrophic collapses, with the historical centres of some settlements being almost completely destroyed. However, such dramatic performance was observed in Amatrice (Fig. 9a) and Arquata d/T, whereas residential buildings in the historical centre of Norcia have shown a much better performance (Fig. 9b), despite ground motion being similar or even more severe in the last settlement (Table 1, Fig. 2).

The effect of damage accumulation played a significant role in defining the actual destruction situation of some settlements, although the difference in the quality of structural details and masonry illustrated in § 2 is decisive for the seismic response of buildings to repeated shocks. For instance, being comparable the ground motion experienced in Norcia and Accumoli on the 24th August and the 30th October (Table 1, Fig. 2), the final state is completely different leading to the almost total destruction of ordinary historical buildings in Accumoli (Fig. 10).

In several cases the main damage mode of the buildings has been the disintegration of masonry, due to a combination of undressed units and very poor mortar quality (Fig. 11). Although delamination of external masonry leaf has been reported in other Italian earthquakes (e.g., Decanini et al. 2004; Augenti and Parisi 2010), it has been extremely common in some settlements of Amatrice, Accumoli and Arquata d/T involving large portions of whole blocks. Therefore, the critical role of mortar has been clearly highlighted by this sequence, with collapses occurring even when the units' assemblage was reasonably accurate at least on the external leaf (Fig. 12), and mortar composition and strength should be always investigated to make an exhaustive assessment (Artioli et al. 2010; Liberatore et al. 2016). Personal communication by an old person in one of the small settlements within the municipality of Amatrice conveyed that at least until 60-70 years ago wall construction took place manufacturing mortar from a soil pit where the excavated ground was mixed with water until proper plasticity was achieved.

Fig. 9. a) Amatrice, after the 24th August event. b) Norcia, after the 30th October event. Snapshots from the movies released by the Firefighters Corps (www.vigilfuoco.tv).

This statement has been confirmed by preliminary studies on mortars from the area of Amatrice, which are composed of a binding fraction mainly constituted by clay minerals, sometimes stabilised by the addition of small aliquots of aerial lime poorly mixed with a soil fraction. Furthermore, mortars' aggregate is often constituted by the sole coarse fraction of the natural soil employed as binder, with consequent poor optimization both of its compositional and granulometric characteristics and proportions with the binder itself. The final result is a set of binding materials with scarce cohesive properties and inadequate adhesive properties with the masonry units, giving at the same time poor stability to the walls due to the swelling characteristics of clays when subjected to water percolation.

Fig. 10. Damage accumulation in Accumoli, via Tito Vespasiano: a) After August 24th, b) After October 30th.

Fig. 11. Poor performance of undressed natural stone buildings in: a) Accumoli, Illica and b) Amatrice, corso Umberto I.

Fig. 12. Masonry disintegration due to poor quality mortar in a reasonably accurate units' assemblage of the external leaf. Amatrice, Cossito: a) Front view, b) detail of masonry on the left-lateral wall.

Fig. 13. Collapse of a masonry building having steel ties combined to poor mortar. a) Amatrice, Petrana; b) Arquata d/T, Piazza Umberto I.

Previous studies in seismic contexts, carried out on mortar samples collected in Onna, Tempera and Sant'Eusanio Forconese, all located near L'Aquila (Artioli et al. 2010; Artioli et al. 2011), also revealed the possible presence of clay, but in a smaller percentage of samples, and with smaller fractions, than those found in the area of Amatrice. These mortar characteristics could at least partially explain the performance found after the 24th August event, worse than that of the 2009 L'Aquila Earthquake. Additionally, several experiments show that undressed natural stone with proper mortar can have substantial seismic strength (e.g., Magenes et al. 2014; Silva et al. 2014; Giaretton et al. 2017).

If disintegration due to poor masonry quality occurs any modelling of building response becomes unreliable (Sorrentino et al. 2017). As shown in Fig. 13, when masonry has such a low strength even the systematic use of steel ties is ineffective. When combined with a reasonable quality masonry, steel ties certainly contributed to preventing collapse (Fig. 3, Fig. 8). Nevertheless, besides the low masonry quality, the limited presence of connections in many buildings, the reduced strength of lateral walls compared to large-units wall intersections (Fig. 14), as well as the presence of intermediate floors having scarce diaphragm effect, poor details at the bearings, and no connections to the walls parallel to beams, should be recalled (Fig. 6).

Media attention immediately after the August event blamed buildings with original roofs replaced with reinforced concrete structures. After being compulsory in case of structural interventions for more than two decades after the 1976 Friuli and 1980 Irpinia Earthquakes, building codes assumed a more careful approach after the performances observed in the 1997-1998 Umbria-Marche sequence (Penazzi et al. 2000). The current seismic swarm has shown again similar responses, with complete collapses of buildings under still monolithic roofs (Fig. 15a) or local effects associated to the compressive failure or out-of-plane response of masonry at the contact with reinforced concrete ring beams. However, there are several examples, such as that in Fig. 13 and in Fig. 16a, of very high damage despite the original timber structures were not replaced. On the opposite side of possible performances there are several cases, such as that of the house in Fig. 15b, which have a replaced reinforced concrete roof but no visible damage. Similarly, there are examples of houses with a timber roof that survived the earthquake (Fig. 16b), especially if timber elements were properly designed and connected to walls (Senaldi et al. 2014). Therefore, it seems that although replacing a timber roof by a reinforced concrete roof has been motivated by past lack of confidence in the original structural, rather than real limitations, such intervention alone cannot explain most of the observed collapses. These failures seem related to a very poor quality of masonry, especially of the mortar (Fig. 12), frequently combined to low maintenance conditions of timber roofs and lack of proper connections in traditional structures.

Fig. 14. Reduced strength of lateral walls compared to large-units wall intersections, Amatrice, Retrosi.

Fig. 15. Replaced reinforced concrete roofs: a) Arquata del Tronto, Pescara del Tronto; b) Amatrice, San Tomasso.

Fig. 16. Timber roofs: a) Castelsantangelo sul Nera, via B. Vittazzi, b) Arquata del Tronto, Pescara del Tronto.

A more radical building activity is that highlighted by the structure in Fig. 17, which has been completely demolished around 1985 and rebuilt using the same natural stone units but a modern mortar. To the satisfactory earthquake performance certainly contributed the ring beams, present at each floor and at opening height at the first storey, but the lack of evident damage suggests an adequate strength of the stonework as well.

Demolition and reconstruction has been observed also in other instances. In Castelluccio di Norcia the building in Fig. 18a presents a natural stone masonry veneer. However, the actual structure is made of hollow clay blocks, as visible in a local gap (Fig. 18b), as observed also in Montegallo and as documented by a previous research on another building damaged by the 1979 earthquake (Binda et al. 2005). The building in Fig. 18 has survived undamaged the August events and despite a second inspection was impossible because the whole historic centre has been made off limits, aerial views after the October events showed that it still stands. The veneer is connected to the blockwork by means of carbon steel rebars (Fig. 18b), which proved effective in the current seismic sequence occurred just after construction, but could be corroded over time. Hence, stainless steel reinforcement is to be recommended.

Fig. 17. Demolished and rebuilt natural stone masonry, resorting to modern mortar and ring beams. Amatrice, San Capone. a) Post 24th August; b) Post 30th October.

Fig. 18. Demolished and rebuilt clay block masonry with connected natural stone veneer. Norcia, Castelluccio di Norcia. a) General view, b) close up of a cavity, with clay block and connection rebar visible within the red frame.

Fig. 19. Demolished and rebuilt plastered clay block masonry. a) General view, b) close up of a cavity, with clay block visible. Norcia, via Anicia intersection with via Cappellini.

A somewhat similar example is that in Fig. 19a, located in the very historical centre of Norcia. The building seems a typical vintage construction, but its plaster finishing covers a hollow clay block structure (Fig. 19b) as a result of a mid 1980s demolition and reconstruction. Interventions such as those just documented have been considered in the past as unacceptable, but the extremely poor performance of entire historical centres and the very high toll in terms of lost human lives suggest that a general reconsideration is necessary. Preservation of environment values (shape and surface aspect of the buildings), while internal structure is replaced, should not be considered out of question, both in the case of collapsed buildings as in the case of documented very poor characteristics of masonry in slightly damaged buildings.

4 PERFORMANCE OF MODERN BUILDINGS

The previous examples of buildings demolished and rebuilt resorting to a blockwork structure highlight the very satisfactory performance of modern masonry. This is the case not only of reconstructions but also of brand new buildings. A well documented example is one located in a small settlement within the municipality of Amatrice, which survived with negligible damage both main events (Fig. 20a-b). The building has a blockwork structure, with vertically perforated clay units (Fig. 20c). Walls are single leaf, with reinforced concrete lintels, and floors are made with precast reinforced concrete beams and hollow blocks (Fig. 20d). According to the most common practice in Italy such floors are partially cast in situ, for which the Italian Building Code (DMI 2008) prescribes a 40-mm thick slab with two-way reinforcement. Similar success stories have been documented by the authors in several settlements of the municipality of Amatrice and by other investigators in that of Norcia (Mosele 2017). Such buildings can be also fairly irregular in plan (articulated layouts with non orthogonal wall alignments) and in elevation (different roof levels), but they are usually just two floors above ground, or three in very limited instances.

It is worth mentioning that, as shown in Table 1, these buildings repeatedly experienced a ground motion severity in excess of those recommended by the Italian code for the life safety limit state (DMI 2008), without suffering the significant damage to structural components and the partial collapses to non structural components accepted by the building standard. Therefore, these building techniques protected not only human life, but also the monetary cost of construction and the continuity of use. Such more than satisfactory performances have been observed also in Emilia in 2012 (Penna et al. 2014), as a consequence of proper masonry quality, adequate construction details, as well as wall density in plan and elevation.

Fig. 20. Clay block masonry building. a) After the 24th August event, b) after the 30th October event, c) close up of a block, d) view of bare wall and floor. Amatrice, San Capone.

Fig. 21. Solid concrete block masonry building. a) After the 24th August event, b) after the 30th October event. Amatrice, viale Saturnino Muzii.

Fig. 22. Solid concrete block masonry (ground floor) and tuff masonry (first floor) building. a) External view, b) Internal view at first floor above ground. Accumoli, Illica.

Although hollow clay blocks are the most used units in the last years, other solutions have been resorted to in the recent decades. An example is given by solid concrete units visible in the top floor of the house in Fig. 17, as well as in the building adjacent to Amatrice historical centre in Fig. 21. This last building, dating back to the mid 1980s, has 600 mm thick walls in the basement, 450 mm walls at ground floor, and 300 mm walls at first floor. It survived the August events without any damage, despite the widespread collapses of nearby standing structures. The October events, on the contrary, caused a heavy rocking response in the piers of the ground floor and moderate shear cracking at the first floor. Overall the performance can be certainly considered code compliant, bearing in mind the severity of the shaking in Amatrice. Similar success histories have been observed in Accumoli and Casale (municipality of Amatrice), whereas in San Lorenzo a Flaviano and Saletta (municipality of Amatrice) performance has been much poorer.

In Illica there is a modern masonry building, having a ground floor made of solid concrete units, and a top floor made of tuff solid blocks (Fig. 22a). Whereas the bottom floor survived the August events with just slight damage, the top storey suffered heavy stair stepped shear cracks (Fig. 22b). This response seems to indicate that mortar had a lower strength of stone units, but the overall performance is still acceptable although less satisfactory of that of the concrete block masonry at ground floor, which is also usually where in plane seismic demands are higher. A better response in a tuff masonry construction has been observed in Accumoli and a somewhat worse in Saletta (municipality of Amatrice), but again without unit cracking and without any collapse.

5 CONCLUSIONS

Between August 2016 and January 2017 nine shallow earthquakes of moment magnitude between 5.0 and 6.5 affected Central Italy, with the single most intense event in Italy since 1980. The sequence involved several municipalities wherein unreinforced masonry buildings are between 78 and 97% of all constructions, whereas the national percentage is 61. The level of damage has been very severe, with sixteen settlements belonging to the municipalities of Amatrice, Arquata del Tronto, Accumoli, Castelsantangelo sul Nera, and Norcia experiencing a cumulative European macroseismic scale intensity larger than IX. Such intensity has not been observed in Italian events of the previous forty years. Ground motion demand in terms of peak ground velocity varied between 35 and 60 cm/s, approximately two or three times what expected for a 475 years return period, and larger than in 2009 in L'Aquila. Pseudoacceleration response spectra show values between once and twice gravity acceleration for an approximate period range of 0.2-0.4 s, typical of two and three storeys unreinforced masonry buildings. Moreover, since October 2016, such large demands acted on structures damaged from previous shocks, causing an important damage accumulation, particularly relevant in Accumoli. Neither the significant shaking, nor a building stock older than national average, can fully explain the extremely severe damage of some settlements, with large portions of whole blocks completely collapsed. Although deficiencies observed in other Italian earthquakes have been surveyed also during this sequence (e.g. lack of proper connections between walls and transversal structures, inadequate effectiveness of masonry interlocking to corner units, defective robustness of horizontal structures) a marked vulnerability of masonry, and particularly due its very poor mortar, has been noticed in the area between Amatrice and Arquata del Tronto. A preliminary compositional comparison with constructions affected by the 2009 L'Aquila earthquake highlighted that the mortar in and around Amatrice has a much larger aliquot of clay minerals and soil as stabiliser, thus contributing to explain the poor cohesion and adhesion observed in the field. The rather low quality of masonry downplayed the role of tie rods, ineffective if masonry disintegrates, or type of roof, either timber of reinforced concrete, with heavier replaced structures contributing to an overall satisfactory performance if vertical structures have adequate strength.

A much better seismic behaviour has been surveyed in the main historical centre of Norcia, which suffered seven earthquakes of Mercalli-Cancani-Sieberg intensity equal or larger than VIII in the last four centuries. Of great relevance is the 1859 event that sparked the formulation of one of the earliest standard for earthquake resistant constructions, with great emphasis on masonry quality (both in terms of overall geometry, unit arrangement and mortar characteristics), as well as connections between structural elements. Moreover, more recent seismic events, especially that in 1979, involved extensive interventions that avoided the catastrophic collapses observed elsewhere in ordinary masonry structures.

In the historical centre of Norcia, but also elsewhere, there are examples of demolished and rebuilt constructions that performed very well. In light of the state of destruction surveyed in many historical settlements, this intervention strategy, frequently considered as too radical in the past, shall be reassessed as a possible compromise between preservation of shape and surface features, as well as protection of human life. Reconstruction with contemporary masonry shall be considered not only where destruction has already occurred, but also when a high vulnerability of the masonry is preventively documented.

A correspondingly satisfactory performance has been observed in modern buildings made of hollow clay blockwork that preserved not only the life of the dwellers, but also the monetary investment cost of construction and continuity of use. This behaviour is related to the adequate masonry quality, the comparatively lighter structures, and the redundancy of the configuration. Such a positive response is an encouraging indication for future building activity, whereas the overall balance within the Central Italy seismic sequence has been very grim for historical unreinforced masonry structures.

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