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ORIGINAL RESEARCH PAPER

Remarks on damage and response of school buildings after the Central Italy earthquake sequence

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Abstract The seismic assessment of the vulnerability of existing public structures, especially school buildings, is a crucial issue in seismic prone countries. Recently, several national and regional programs and activities have focussed on the mitigation of Italian public buildings. They promote the scheduling of public buildings' structural safety assessment and, when needed, the design and execution of strengthening interventions. Nevertheless, the three strong earthquakes that occurred in the last decade in Italy, Abruzzo (2009), Emilia (2012), and Central Italy (2016), confirmed the vulnerability of school buildings and the social importance of their quick re-opening after a damaging earthquake. In the present paper, the activities carried out on 1514 school building structures in the aftermath of the 2016 Central Italy earthquake sequence are reported and analysed. According to survey data collected by post-earthquake usability inspections, the paper analyses the school buildings characteristics, damage level and extent to structural and non-structural components as well as the correlation between seismic intensity and observed damage.

Keywords School buildings · Earthquake · Usability and damage assessment · Seismic risk

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1 Introduction

School buildings play a critical role for social and cultural life of people. In seismically active regions, several school buildings need strengthening interventions, because seismic codes and seismic hazard classifications have evolved over time and many structures were built before the development of modern seismic design provisions or not considering seismic provisions at all. Moreover, the architectural configurations of school buildings, consequent to the several functions to be carried out inside them, result in irregular structures with intrinsically unfavourable seismic behaviour (Dolce 2004). In recent years, a significant effort has been devoted in several nations to projects for seismic rehabilitation of school buildings, including the allocation of funds to regions of high seismic hazard (Alexander et al. 2015).

In North America, the Canadian government developed a suitable program to improve seismic safety of school buildings; the current Seismic Mitigation Program, managed by the Ministry of Education, covers costs for mitigation of vulnerability of both structural and non-structural components of public schools in British Columbia. The original estimate of the cost of the structural component was $1.5 billion and the program goals called for the intervention on over 700 schools in the zones of highest seismic risk in the province. In addition, the ministry currently provides $5 million annually for non-structural seismic mitigation to the boards of education located in the high-risk seismic zones (Ventura et al. 2017). In California (USA), from a preliminary safety assessment of 9659 pre-1978 school buildings made in 1999, the final report shows 7537 potentially vulnerable buildings requiring detailed seismic evaluation. The estimated cost of retrofit was $4.5 billion (State of California 2002). In Mexico, education authorities initiated a major reconstruction programme in the capital following the 1985 earthquake in Mexico City. The project included strengthening interventions or rebuilding of units located in high-risk zones, in compliance with construction codes and regulations enforced after the events of September 1985. Between 1986 and 1991, 2400 structures were rehabilitated. The Natural Disaster Fund is supported by the federal, the state and the municipal governments to provide public domain infrastructure in case of a disaster. This fund provides a temporary resource until the insurance premium is collected; the goal is to restore the damaged property and to implement preventative measures (Reyna 2004).

In East Asia, Japan, the school seismic safety has been deeply discussed in these years but only in 2005 the Ministry of Education (MEXT) started the assessment of safety level of 125,000 public school buildings. It resulted in about 25% of school structures safe, but 48,000 older school buildings were found needing assessment or retrofitting. In 2008, 229 billion JPY were allocated by MEXT to meet the goal of the retrofit of all the highest-risk school buildings within 4 years (Rodgers 2012).

In Europe, Turkey, the Istanbul Seismic Risk Mitigation and Emergency Preparedness Project (ISMEP) (with loans from World Bank and EIB) allowed a risk mitigation program on school buildings to be set up. In 2007–2008, the safety assessment of more than 600 school complex was carried out along with the works for retrofitting 250 schools and reconstruction of 36 schools. In 2009, further 450 schools were scheduled for retrofitting (Gülkan 2004).

The UNESCO (United Nation Educational Scientific and Cultural Organization) recently started to promote a comprehensive approach to disaster risk reduction, which focuses on themes related to school safety and disaster management (http://www.unesco.org). Italy is a region of moderate to high seismicity with a significant number of changes of seismic regulatory codes and design provisions. The first seismic building code was the royal decree of 1909 (R.D. 1909), made after the 1908 Messina earthquake (Fralleone et al. 1999), including site-selection criteria and structural typologies as well as details provisions for new buildings. After the 1915 earthquake in the Abruzzo region, seismic provisions were updated and refined, introducing the value of the horizontal seismic forces R.D.L (1915). In the following years, no major changes in seismic provision were approved until 1975, when a response spectrum was introduced to perform dynamic or static analyses, with a horizontal force obtained as a function of seismic zonation, soil type, structural system, building structural period, and seismic weight. Thus, evolutions of regulatory provisions were undertaken over the last century once the understanding of the effects of earthquakes on structures and the knowledge of seismic hazard improved (Grant et al. 2007). In the meanwhile the seismic hazard zonation evolved very slowly, so that until 1980 only 25% of the Italian territory had been classified as seismic zones. That is why a large proportion of buildings in Italy have been designed without seismic provisions or in compliance with obsolete codes, with underestimation of the seismic actions and of their effects. This was clearly and tragically demonstrated by the Molise earthquake that occurred in southern Italy in October 2002: 27 children and one teacher were killed in the collapse of a primary school in San Giuliano (Augenti et al. 2002; Bazzurro and Maffei 2004). After the Molise earthquake, the public opinion focused on the problem of high seismic vulnerability of schools. Five months after the earthquake, a new seismic code was introduced by an ordinance of the Prime Minister (O.P.C.M. 3274 2003) and the whole Italian territory was considered as subjected to seismic hazard, through the definition of four seismic zones. Furthermore, the same ordinance stated that the seismic vulnerability of all public strategic and critical buildings, including schools, in medium and high hazard areas, had to be evaluated within the next five years, in order to set up a seismic rehabilitation programme. The evaluation of the seismic vulnerability of schools was started independently by several local administrations. In 2005, €460 million were allocated to the seismic assessment and retrofit of schools (Grant et al. 2007). The funds were distributed amongst the different Italian Administrative Regions as a function of the number of school buildings located in each seismic area. Further funds were allocated for structural and non-structural rehabilitation and seismic retrofit. Among them €20 million per year, starting from 2008, for full seismic retrofit. However, the initiative was clearly not enough to significantly reduce the seismic risk of school buildings; indeed, Italy has about 60,000 public and private school buildings, with a large percentage built with obsolete seismic code provisions and located in areas of high seismic hazard. The strong earthquakes which occurred in the last decade, Abruzzo (2009), Emilia (2012) and, very recently, Central Italy (2016–2017), confirmed the vulnerability of existing structures and school buildings (Braga et al. 2011; Di Ludovico et al. 2012, 2017a, b, c; Frascadore et al. 2015; Dolce et al. 2016; Del Gaudio et al. 2017). The paper focuses on the analysis of the response of school buildings in the recent seismic sequence of Central Italy; in particular, it illustrates and discusses the correlation between buildings structural typology, seismic intensity and observed damage as well as the influence of seismic sequence parameters on the school buildings overall damage.

2 In-situ surveys on schools in the aftermath of the central italy earthquakes

A first earthquake (Mw6.0) hit central Italy regions (i.e. Abruzzo, Lazio, Umbria, Marche) on 2016-08-24 at 01:36:32 GMT; the quake epicentre was close to Amatrice, Accumoli and Arquata del Tronto and caused diffuse building collapses and about 300 casualties. After 2 months, on 2016-10-26, two events, Mw5.4 (17:10:36 UTC) and Mw5.9 (19:18:06 UTC) extended to the NW the seismogenic volume. After 4 days, on 2016-10-30 at 06:40:18 UTC an event of Mw6.5, struck the area corresponding to the Sibillini mountains with epicenter close to Norcia, Umbria Region. The latter earthquakes provided extensive damage especially to many historical buildings but no deaths had been recorded.

On 2017-01-18 a short sequence of four Mw5+ earthquakes struck 25 km northwest of L'Aquila, starting at 09:25:40 UTC with Mw5.1 and ending at 13:33:36 UTC, with the fourth tremor of magnitude M5.0. The two strongest events occurred at 10:14:09 UTC, with Mw5.5. and 11 min later with Mw5.4.

The Italian regions hit by the earthquake sequence and the shake maps of the four main shocks of the sequence, Mw6.0 August 24 2016, Mw5.9 October 26 2016, Mw6.5 October 30 2016, and Mw5.5 January 18 2017 are depicted in Fig. 1.

In the aftermath of the earthquakes inspections were immediately started to ascertain damage and usability of buildings, using the AeDES ''Building Operability and Damage during the Post-Earthquake Emergency'' survey form (Baggio et al. 2007), whose most recent official version can be found in (DPCM 14.05.2015). Priority was given to public buildings, primarily schools. The AeDES form is filled on the basis of visual in situ inspection of the building. According to the AeDES form, buildings can be classified into the main following categories, according to the immediate or future usability of the undamaged/damaged building: A—Usable buildings; B or C (B/C in the following)—Building usable only after short-term countermeasures or partially usable; E—Unusable building.

At the end of the sequence, school surveys involved the inspection of 1514 buildings to evaluate structural and non-structural damage and immediate building usability. Note that the usability form refers to one structural unit, i.e. one building. A detailed discussion on the most frequent observed damage types on structural and/or non-structural elements of masonry and Reinforced Concrete (RC) school buildings is reported in Di Ludovico et al. (2017c). In the following, the discussion focuses on the analysis of the usability rating, the level and extent of damage to structural and non-structural components, as well as their correlation with the seismic intensity in terms of maximum Peak Ground Acceleration (PGA) recorded during the seismic sequence.

3 Usability rating of school building structures

In the post-earthquake emergency phase of the first main shock (August 24, 2016, at 03:36 AM local time) the total amount of inspections carried out by experts of several institutions involved 872 school buildings (i.e. buildings and sports facilities of pre-primary, primary, high schools and universities) in four regions of central Italy: Abruzzo, Lazio, Marche, and Umbria.

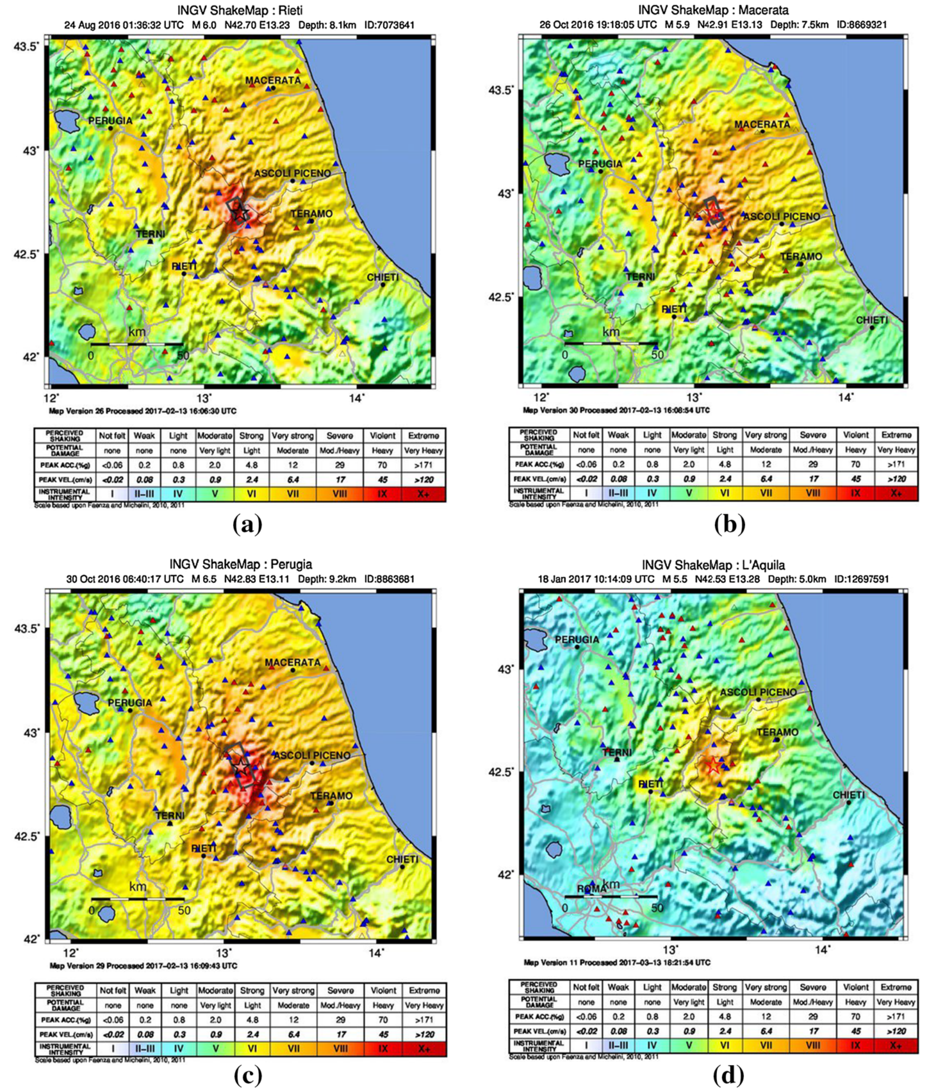
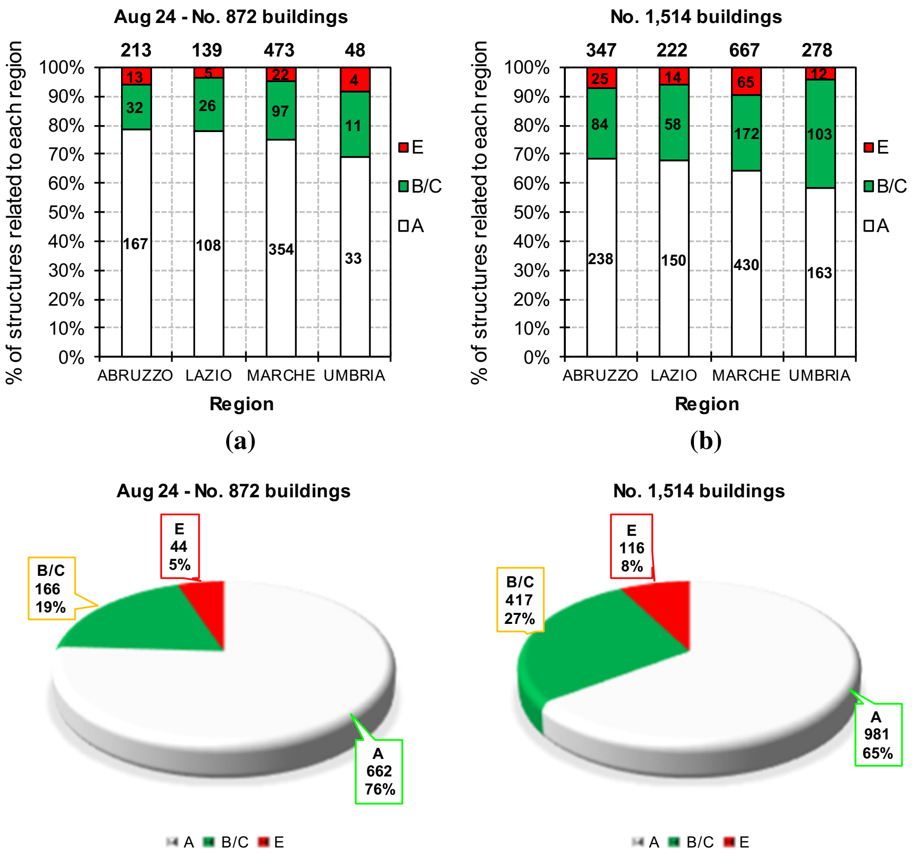


Fig. 1 MCS instrumental intensity shake maps of the four main shocks of the sequence provided by INGV: **a** M6.0 August 24, 2016; **b** M5.9 October 26, 2016; **c** M6.5 October 30, 2016 and **d** M5.5 January 18, 2017

After the entire seismic sequence, the surveys involved 1514 school buildings, many of which were reviewed in the aftermath of October 2016 and January 18, 2017, seismic events. Note that 447 out of 1514 buildings were re-inspected during the seismic sequence.

Figure 2a, c show the number of inspected buildings in each region in the post August 24, 2016, event as well as the percentage of structures classified as usable (i.e. A rating) or unusable (i.e. B/C usability rating for buildings/structures with limited or no structural damage, but with severe non-structural damage, and E usability rating for those with high structural or non-structural risk, high external or geotechnical risk, respectively) according to the AeDES form. In particular, the usability rating is reported as a percentage of



(a) (b)

(c) (d)

Fig. 2 Number of inspected school buildings in each region and percentage of structures classified as usable or unusable after: August 24, 2016 (**a**, **c**); the entire seismic sequence (**b**, **d**)

structures located in a given region in Fig. 2a and with reference to the whole stock of buildings investigated after the event, namely 872 buildings, in Fig. 2c. In terms of usability assessment, 662 school buildings, corresponding to 76% of the dataset, were assessed with usability rating A. The remaining 210 buildings resulted unusable (rating B/C for 166 buildings, about 19% of the dataset, and 44 buildings with rating E, about 5% of the dataset).

Figure 2b, d summarize the data collected after the entire seismic sequence on a total of 1514 buildings: 65% usable and 35% unusable (i.e. 27% B/C and 8% E rating, respectively). Thus, a percentage increase of about 10% of unusable buildings was recorded at the end of the sequence with respect to surveys related to the first earthquake, while the total number of unusable buildings (B/C or E) raised from 210 to 533. The data collected show that the number of in situ inspections significantly increased in Umbria region, which is the region of the epicenters of the October earthquakes. Nevertheless, Fig. 2b shows that the most severe damage was detected on structures located in the Marche Region (about 10% of E usability rating), while slight damage to structural or non-structural members were observed in a significant percentage of school structures of the Umbria Region (about 37% with B/C usability rating).

Table 1 summarizes the usability rating of schools focusing on the influence of the structural type. It shows that 52% of the total amount of 1514 structural units under investigation concerns RC buildings, 35% masonry buildings, while the remaining 13% involves buildings with a mixed structural type (i.e. comprising RC and masonry structural members), steel structure or other types. RC is the most common structural type in buildings with usability rating A, B/C; by contrast, masonry is the most common structural type in the case of buildings with usability rating E.

The usability rating distribution of school buildings related to different construction age periods are presented in Fig. 3a, b for RC and masonry buildings, respectively. The construction age is classified according to thirteen periods as adopted in the current AeDES form. Note that the construction age period is unknown for 23 out of 785 RC school buildings and 10 out of 525 masonry school buildings, respectively, thus Fig. 3a, b refers to 762 and 515 RC and masonry buildings, respectively. As expected, the percentage of unusable (i.e. B/C or E rating) buildings decreases as a function of construction age, apart from any other consideration related to design criteria and earthquake intensity that will be made in the following paragraph.

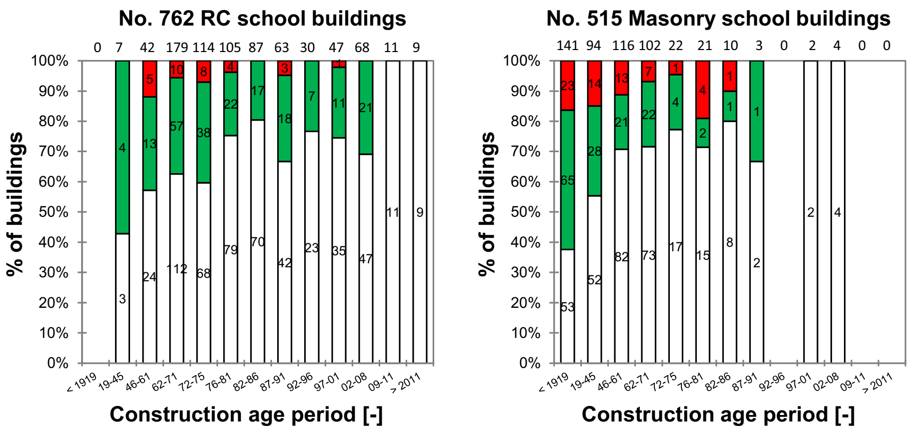
4 Usability rating versus earthquake intensity

The distribution of usability ratings of the school buildings as a function of the maximum Peak Ground Acceleration recorded during the seismic sequence is depicted in Fig. 4. For each school building, the corresponding maximum PGA value is extrapolated from the shake maps provided by INGV (Istituto Nazionale di Geofisica e Vulcanologia, INGV, http://shakemap.rm.ingv.it/shake/index.html). More details about how local soil conditions are kept into account in the evaluation of PGA that affected the dataset of schools can be found in Michelini et al. (2008).

Figure 4 shows the number of structures that experienced different maximum PGA as well as the percentage of structures classified as usable (i.e. A rating) or unusable (i.e. B/C or E usability rating) according to the AeDES form. The percentage of usable school structures inspected after the seismic sequence, ranges from 68 to 14% with increasing

Table 1 No. of school structures in each usability rating class and structural types

Building stock	Structural type	No. of structures	Usability rating	No. of buildings	% of buildings
1514	RC	785	A	539	69
			B/C	214	27
			E	32	4
	Masonry	525	A	314	60
			B/C	146	28
			E	65	12
	Other types	204	A	128	63
			B/C	57	28
			E	19	9

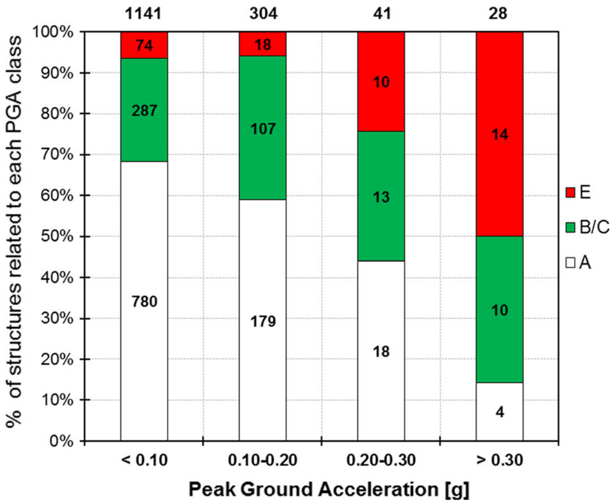


(a)

(b)

Fig. 3 Distribution of usability ratings of the school structures as a function of the construction age period: **a** RC buildings; **b** masonry buildings

Fig. 4 Distribution of usability ratings of the school structures as a function of the maximum Peak Ground Acceleration recorded during the seismic sequence



PGA from less than 0.10 g up to more than 0.30 g. As expected, the distribution of usability rating becomes more severe with increasing PGA, up to 36% (for B/C rating) and 50% (for E rating), respectively, in the case of PGA greater than 0.30 g.

According to the Italian Building Standards NTC08 (2008), the reference life related to a school building is 75 years (nominal life of 50 years and importance class coefficient 1.5). The return periods, T_R, for service and ultimate limit states are the following: $T_R = 45$ years for the Operational Limit State (Frequent Event, 81% probability of exceedance, named SLO in the following); $T_R = 75$ years for the Damage Limit State (Occasional Event, 63% probability of exceedance, named SLD); $T_R = 712$ years for the Life Safety Limit State (Rare Event, 10% probability of exceedance, named SLV); $T_R = 1462$ years Collapse Prevention Limit State (Very Rare Event, 5% probability of exceedance, named SLC). The relevant design a_g value ranges (for ideal stiff soil—

horizontal surface conditions) related to such limit states in the regions struck by the earthquake sequence are: SLO, 0.025–0.100 g; SLD, 0.035–0.125 g; SLV, 0.065–0.300 g; SLC, 0.075–0.380 g. Since seismic codes and seismic hazard classifications have evolved over time, several school buildings of the dataset were built before the development of modern seismic design provisions or for gravity load only (i.e. not considering seismic provisions at all). Thus, in the following the analyses refer to two classes of structures: ‘‘gravity load’’ stands for structures built in a municipality before its seismic classification and “seismic load” for structures built in a municipality that was already classified as ‘‘seismic’’ at the time of the construction. Out of 1514 school structures, 802 resulted designed for gravity load only corresponding to 53% of the dataset. Note that in the remaining portion of the dataset (i.e. 47% of structures in the class “seismic load” most of the structures were designed to sustain horizontal actions but according to obsolete seismic provisions with no detail requirements for ductility.

Figure 5a–d show the location of each geo-referenced usable or unusable school building on the Italian seismicity map according to the NTC08 (2008) related to different return periods. In particular, each figure depicts the location and the relevant usability rating of structures that experienced a maximum PGA during the seismic sequence within the design a_g class related to SLO (Fig. 5a), SLD (Fig. 5b), SLV (Fig. 5c), and SLC (Fig. 5d).

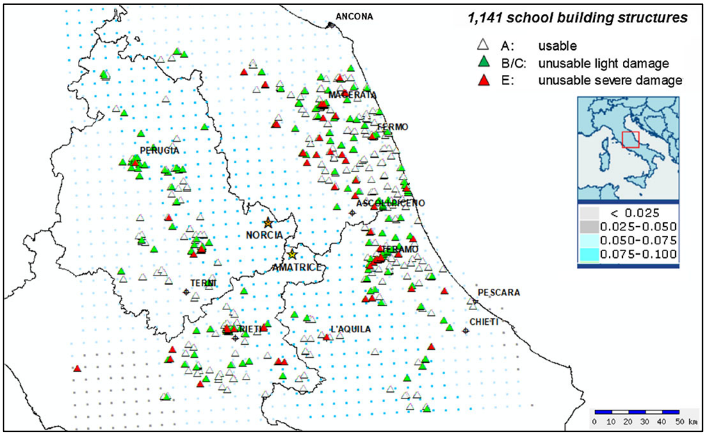
The actual acceleration records that are mentioned below were made available by the Italian Accelerometric Network (RAN), managed by the Italian Department of Civil Protection. Note that they are affected by the soil conditions associated to each station.

Figure 5a reports the school structures located far from the epicentre, where the shake map PGA values are in the range 0.025–0.100 g (i.e. SLO for design purposes). It shows that no significant damage or no structural damage was typically detected in the surveyed buildings; in particular 64 and 72% of buildings resulted usable for ‘‘gravity load’’ and “seismic load” classes, respectively. The usability rating B/C involved 27 and 23% of the buildings in the ‘‘gravity load’’ and “seismic load” classes. Only 74 structures (51 designed only for gravity load and 23 seismically designed, respectively) out of 1141, corresponding to 9 and 5% of the datasets resulted unusable with strong damage (rating E). Note that a significant part of such structures was affected by pre-existing damage on structural and/or non-structural elements, which has been amplified by the 2016 earthquake sequence.

Figure 5b reports the school structures located in the area where the shake map PGA values range is 0.075–0.125 g (i.e. SLD for design purposes) with a maximum record of PGA = 0.119 g. Out of 155 structures, 60 designed only for gravity load and 37 designed with seismic provisions resulted usable (54 and 84% of the datasets, respectively) while 54 structures, 47 “gravity load” and 7 “seismic load” (42 and 16% of the datasets, respectively) showed a slight to moderate damage (B/C usability rating). Finally, significant damage (E rating) was only detected in the “gravity load” class for 4% of the dataset.

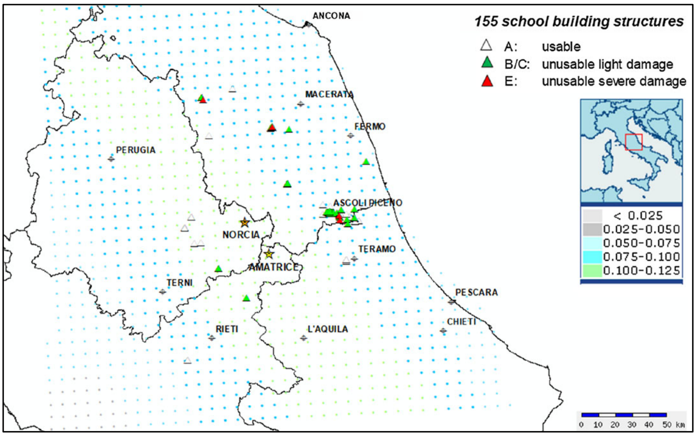
Figure 5a, b clearly shows that, especially for PGA values in the range of SLD for design purposes, the behaviour of buildings designed to sustain horizontal actions (even if lower than those adopted in modern design calculations) was definitely better than that of gravity load schools.

Figure 5c shows school structures mainly located near the epicentral area, where the PGA reached a maximum shake map PGA value of 0.300 g. It is worth noting that even for seismic action comparable to those used in the design of ultimate limit state (SLV), 69% of the structures seismically designed in the dataset resulted usable, while 31% resulted unusable but with 29% of structures affected by slight damage. By contrast, the distribution



Building stock	No. of stuctures	Usability rating	No. of buildings	% of buildings	No. of stuctures	Usability rating	No. of buildings	% of buildings
	GRAVITY LOAD				SEISMIC LOAD			
1,141	586	A	378	64%	555	A	402	72%
		B/C	157	27%		B/C	130	23%
		E	51	9%		E	23	5%

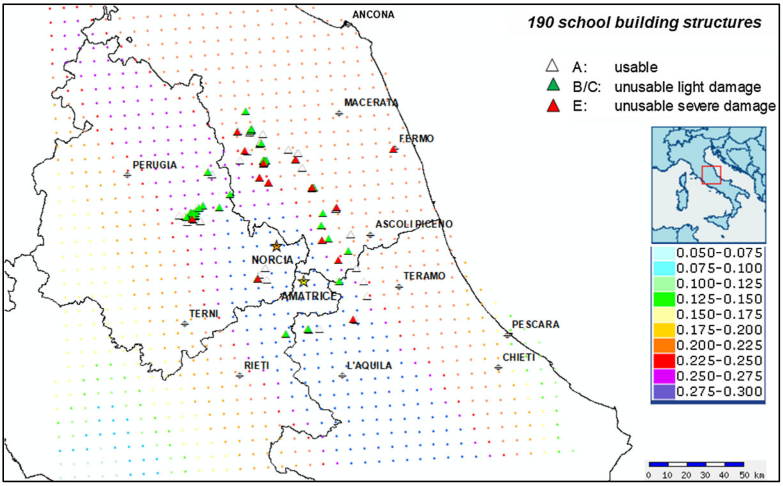
(a)



Building stock	No. of stuctures	Usability rating	No. of buildings	% of buildings	No. of stuctures	Usability rating	No. of buildings	% of buildings
	GRAVITY LOAD				SEISMIC LOAD			
155	111	A	60	54%	44	A	37	84%
		B/C	47	42%		B/C	7	16%
		E	4	4%		E	0	0%

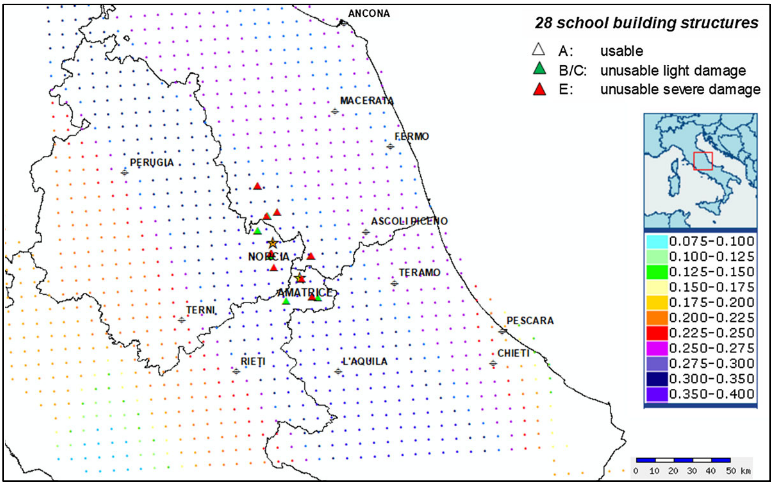
(b)

Fig. 5 **a** Spatial distribution of school structures with recorded PGA within the a_g range related to Operational Limit State (SLO) on the seismic hazard map. **b** Spatial distribution of school buildings with recorded PGA within the a_g range related to Damage Limit State (SLD) on the seismic hazard map. **c** Spatial distribution of school buildings with recorded PGA within the a_g range related to Life Safety Limit State (SLV) on the seismic hazard map. **d** Spatial distribution of school buildings with recorded PGA within the a_g range related to Collapse Prevention Limit State (SLC) on the seismic hazard map



Building stock	No. of stuctures	Usability rating	No. of buildings	% of buildings	No. of stuctures	Usability rating	No. of buildings	% of buildings
	GRAVITY LOAD				SEISMIC LOAD			
190	98	A	37	38%	92	A	63	69%
		B/C	39	40%		B/C	27	29%
		E	22	22%		E	2	2%

(c)



Building stock	No. of stuctures	Usability rating	No. of buildings	% of buildings	No. of stuctures	Usability rating	No. of buildings	% of buildings
	GRAVITY LOAD				SEISMIC LOAD			
28	7	A	0	0%	21	A	4	19%
		B/C	0	0%		B/C	10	48%
		E	7	100%		E	7	33%

(d)

Fig. 5 continued

of usability rating for structures designed only for gravity load provides: 38% usable and 62% unusable (i.e. 40% B/C and 22% E rating, respectively).

Figure 5d reports the school structures located in the epicentral area where the shake map PGA values attained a maximum of 0.74 g, which is far higher than a_g values that are considered by the Italian building code NTC08 at the school site for the SLC limit state, that is in the range 0.075–0.380 g. Although the dataset is limited (i.e. 28 structures corresponding to about 2% of the entire dataset), no severe structural damage was found in 14 structures designed with old seismic provisions (i.e. 4 structures usable and 10 slightly damaged) out of 28 inspected structures. This dataset mostly includes RC school buildings built after the '60s or masonry structures seismically retrofitted after previous earthquakes. Note that 100% of gravity load structures corresponding to 7 structures showed severe damage.

The frequency distribution of damage level of school buildings were clearly affected by several parameters involving the structural seismic behaviour (i.e. in plan and elevation regularity or irregularity, type of horizontal structures, construction age, number of storeys, pre-existing damage, construction quality, and previous strengthening interventions) as well as the seismic demand in terms of earthquake intensity. However, in general, for most of the school buildings, especially for the class "seismic load", the performances matched with expectation related to current seismic design code NTC08 provisions, although very few of them were designed according to such provisions.

5 The role of the vulnerability: some examples

Results of the usability assessment on school buildings can have significant impact on the life of a town, in particular if it is a small community, where school plays a key social role. Indeed, in case of unusable school building (E rating), school activities and students need to be relocated in either temporary structures or usable school buildings of other towns with remarkable impairments for both students and families. Further, the downtime duration depends on the level and extent of damage, which, in turn, determine both time and cost of repairing and strengthening of buildings.

In this framework, it is worth highlighting that the observed damage on school buildings and the usability assessment results above reported do not only depend on the seismic intensity, but also the vulnerability has a significant role, as seen in the previous paragraph.

In particular, as better described below, although some structures were subjected to low seismic intensity, they were severely damaged and, consequently, classified as unusable with E rating. Moreover, the vulnerability of non-structural elements played a remarkable role, also in seismically designed buildings. Indeed, although non-structural elements represent a remarkable share of the whole building cost and a source of risk for life safety in case of collapse (Braga et al. 2011), these components are generally neglected in the safety verifications. Conversely, the adopted solutions mainly depend on the architectural design and thermal/sound insulation requirements.

In order to better highlight the role of the vulnerability on the observed damage and the related usability rating, four unusable school buildings (E rating) having different structural types and subjected to very different earthquake intensities are analysed.

Specifically, the *I* case is the "R. Battaglia" school, a RC building in Norcia (5 km away from the Mw6.5 event's epicentre), where a maximum ground acceleration of 0.48 g (soil type B, according to the NTC2008 Italian seismic code) was nearby recorded during the October 30 event by a RAN station.

The *II* case is the “Villa Reatina2 school in Rieti (RC building, 45 km away from the Mw6.0 epicentre), where on the August 24 event 0.06 g (ground type D) was nearby recorded.

The *III* case is the “B. Tucci” school, a URM building in Acquasanta Terme (17 km away from the M6.0 event’s epicentre and 25 km away from the Mw6.5 one), where a maximum ground acceleration of 0.29 g (soil type B) was nearby recorded during the August 24 event.

Finally, the *IV* case is the municipal nursery school, a URM/RC building in Force (35 km away from both the Mw6.0 and Mw6.5 events’ epicentres), where a maximum ground acceleration of 0.07 g was nearby recorded during the October 30 event.

5.1 RC school building in Norcia (max PGA = 0.48 g)

The Norcia’s school has 4 RC structures seismically separated: two of them host the teaching rooms (number of storeys ranging from 2 to 3), one is the gym changing room (one storey only) and another one is the gym structure (one storey, large span structure), Fig. 6. All buildings were seismically designed and made up back to the year 2000. It is worth noting that Norcia was classified as seismic in 1962.

After the August 24 earthquake, all the structures were inspected for the usability assessment. The gym changing room structure was assessed as usable (i.e. A rating), the structures of the teaching rooms were temporarily unusable but usable with short-term countermeasures (i.e. B rating, mainly due to slight damage to internal partitions), while the gym structure was assessed as unusable (i.e. E rating). The new post-earthquake usability assessment carried out after the October earthquakes confirmed all the previous results.

Although poor information are generally available on the Norcia’s school, a special focus on the gym structure can be done. In particular, it has rectangular in-plane shape, with area of about 900 m^2 and 10 m high. The resisting structure consists of one way frames made up with arched beams of lamellar wood supported by RC columns. Infill panels are made up with bricks of pumice concrete.

Although the maximum PGA recorded in Norcia on the October 30 event was very high ($a_g = 0.48$ g), no structural damage was observed on all structures. On the contrary, a significant damage was found on the infill walls due to both significant slenderness and


(a) (b)

Fig. 6 The gym structure: external (**a**) and internal view (**b**) poor connection with the surrounding resisting members of the frames. To this purpose, Fig. 7 shows cracks due to the separation of the external layer from the structural frame.

5.2 RC school building in Rieti (max PGA = 0.06 g)

The "Villa Reatina" primary school of Rieti is a RC structure built in the '70 s with inadequate antiseismic criteria. To this purpose, it is worth highlighting that the territory of Rieti was partially classified as seismic in 1915 (after the Avezzano earthquake) while it was completely classified as seismic in 1983. From the available information, no structural intervention was made up in the past.

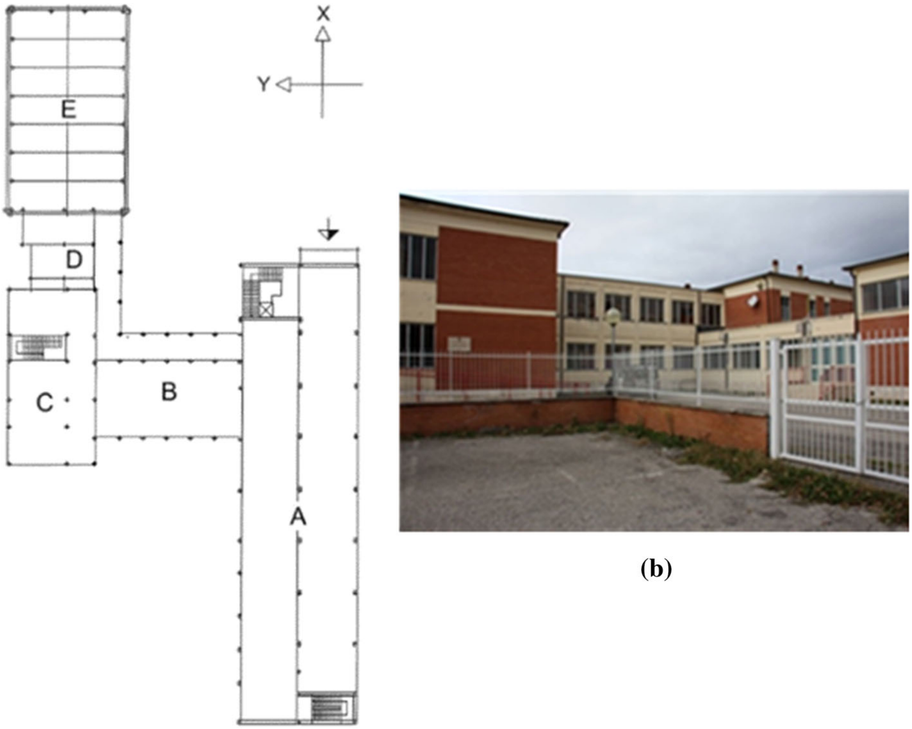
The structure has irregular in-plane shape with two 3.3-m-high storeys in elevation, and area of about 1100 m^2. Resisting system is made up of RC frames bearing the slabs without beams along the transverse direction. After the the post-earthquake survey, the school was unusable (i.e. E rating). Although no structural gap are present between the different blocks of the structures (Fig. 8), for the gym building (block E) a rating B (temporarily unusable but usable with short-term countermeasures) was assessed.

RC resisting elements suffered moderate structural damage. In particular, at the first storey, cracks involving the section end of some beams of the block A were observed (Fig. 9a). According to the AeDES survey form, a D2-D3 damage level was evaluated. Similarly, cracks were observed in some beams and columns at the upper storey (Fig. 9b, c). Smooth bars (Fig. 9d) were used with low percentage of both longitudinal and transverse reinforcements.

As for non-structural elements, cracks in both infill and partition walls were observed, in particular for the panels at the second storey.

It is worth noting that the high seismic vulnerability of the Rieti's school was previously assessed in the framework of the study promoted by the O.P.C.M. 3274 law (2003). In particular, a risk index (i.e. capacity to demand ratio at the life safety limit state) close to zero (i.e. high risk) was calculated.

Fig. 7 Separation of the external layer of infill panels



(a)

(b)

Fig. 8 Layout (**a**) and external view of the school (**b**)

5.3 URM school building in Acquasanta Terme (max PGA = 0.292 g)

Two different surveys were carried out on this structure, one after the Mw6.0, August 24 event and the other one after the two events of October 2016 (Mw5.9 and Mw6.5). This building is located on a slight slope in the historic centre of Acquasanta Terme. It is a pre-II-world-war two stories URM structure detached from other buildings along all its sides, with a surface of approximately 700 m^2 per floor. No significant variations of its structural scheme were observed through the years. The complex consists of two joined buildings (Fig. 10): the school (Building A, see red box with dashed line) and the computer laboratory (Building B). The masonry of the main block (i.e. Building A) was built with a vertical alternation of irregular travertine stones and clay brick courses (with spacing approximately 1 m). The RC roof is non-thrusting and the floor are composed by RC hollow core slabs. All the partitions are made of solid clay brick masonry. The entrance of the building is roofed by a RC portico.

The first visual inspection after the Mw6.0 earthquake revealed significant damage to more than 2/3 of the vertical load bearing elements (masonry piers) (Fig. 11) and the nonstructural partition walls (Fig. 12). Namely, the structure had shear cracks in many of the load bearing walls, likely, the inertia force that loaded the structure during the first event was close to the maximum strength of the building. Damage to spandrels was also observed. The most evident damage was due to the interaction between the URM piers and the RC slabs, both at the first and the second floors (Fig. 13). The stairway structure shows

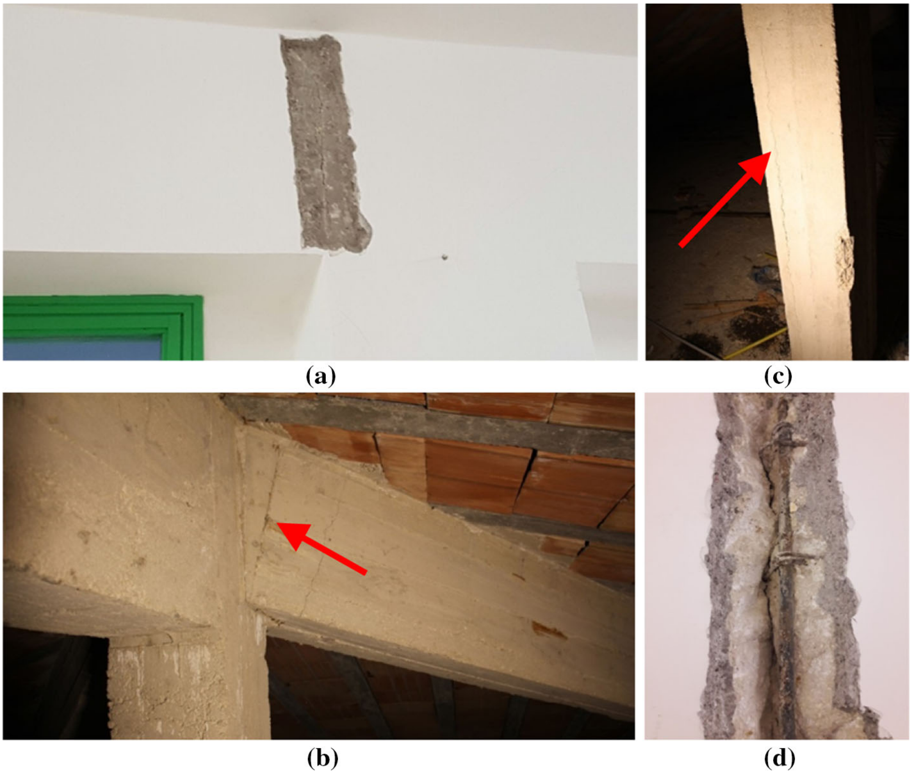


Fig. 9 Cracking failure at the end of beams (**a**, **b**) and columns (**c**). Smoot bars with poor transverse reinforcement (**b**)

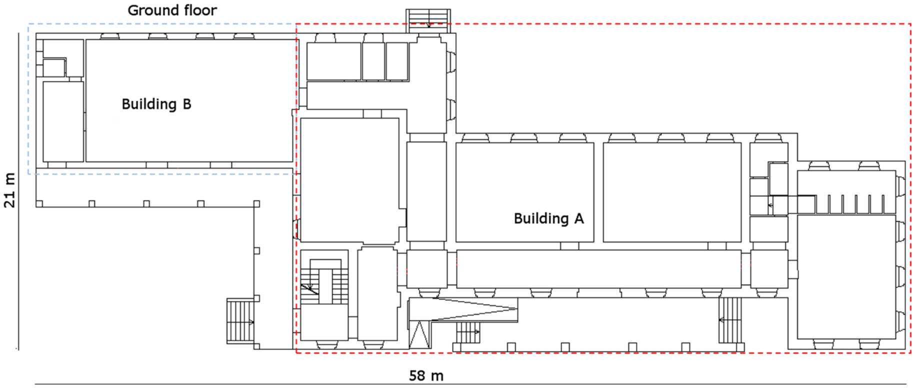


Fig. 10 Ground floor plan view of URM building school of Acquasanta Terme: school building, Building A (dashed red line box) and laboratory building (Building B)

minor damage after the first event; a slight aggravation was reported after the two October events. Falling of plaster and internal objects was observed during the inspections. The detailed visit of the structure after the two October events showed a general worsening of


(a) (b)

Fig. 11 Shear crack in a second floor pier: situation after Mw6.0 event (**a**) and after Mw5.9 and 6.5 events (**b**)

Fig. 12 Damage on 24-cm-thick wall after Mw5.9 and 6.5 events

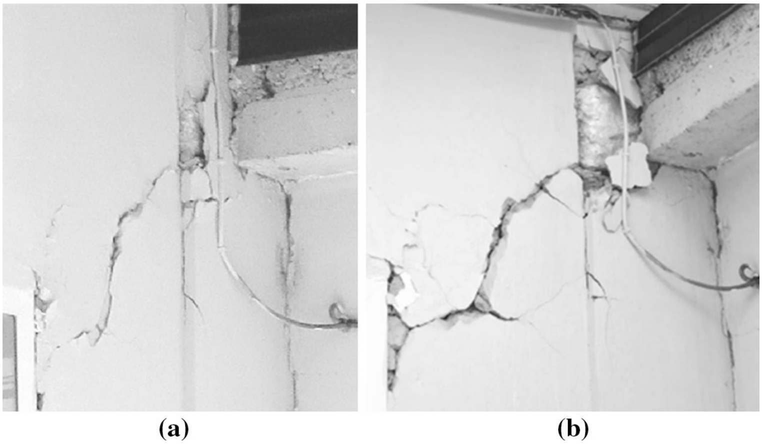

(a) (b)

Fig. 13 Pounding damage: situation after Mw6.0 event (**a**) and after Mw5.9 and 6.5 events (**b**)

the damage, both in terms of crack enlargements and plaster falls. In any case the crack pattern resulted to be substantially the same as reported during the first survey. No evidence of foundation settlements was observed after the three events.

5.4 URM school building in Force (max PGA = 0.065 g)

Like in the previous example, two different surveys were carried out, after the Mw6.0 August 24 event and the two events of October 2016 (Mw5.9 and Mw6.5), respectively. The nursery school of Force was hosted by an isolated URM building positioned on a hill ridge near the historic centre of the town. This two storey building was completed in 1910 and expanded in 1970 by means of a RC structure on the back side of the complex. The extension is about 600 m^2 per floor (Fig. 14). The original structure has load-bearing URM walls (see blue box with dashed line), composed of double-leaf rough-finished stone masonry with very poor lime mortar (Fig. 15a). The floors and the roof are very

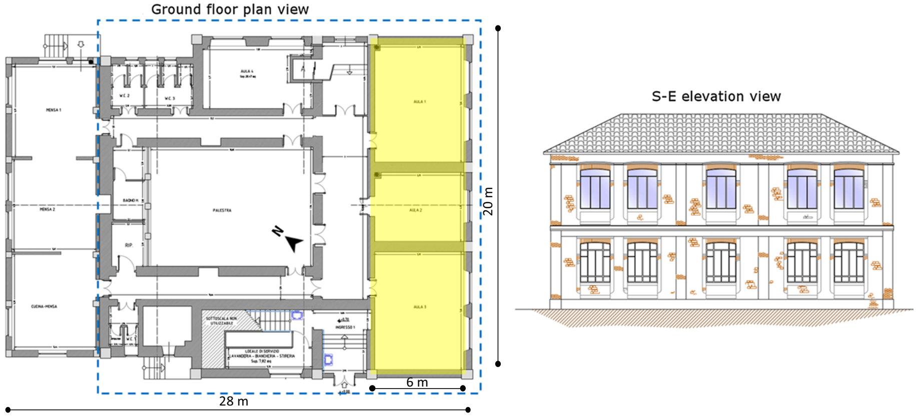


Fig. 14 Ground floor plan view and South/East elevation view of URM/RC building school of Force: the URM part in the dashed blue line box and the most damaged portion highlighted in yellow


(a) (b)

Fig. 15 Double-leaf stone masonry with poor mortar constituting the older part of the building (**a**), damage on a stone URM wall: situation after the Mw6.0 event (**b**) (almost identical also after the Mw5.9 and 6.5 events)

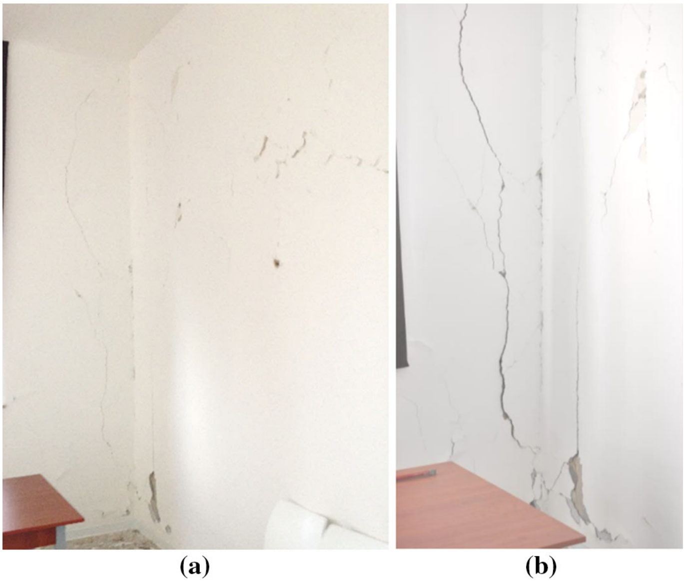


Fig. 16 Damage at the South corner of the building (inside): situation after the Mw6.0 event (**a**) and after the Mw5.9 and 6.5 events (**b**)

heterogeneous, presence of RC hollow brick slabs as well as timber floor and roof are reported. In particular, the oldest portion of the complex (resulted to be more vulnerable) was retrofitted in 1989 by using RC floors and roof.

Despite the relatively low PGA (0.049 g), the first visual inspection after M6.0 earthquake revealed significant damage to large sections of the vertical load bearing elements, especially shear cracks in masonry piers (Fig. 15b) and triggering of out-of-plane wall mechanism at the South corner of the building (Fig. 16a). This mechanism was further reactivated by the October earthquakes, as demonstrated by the worsened crack pattern noticed during the second survey after Mw5.9 and Mw6.5 earthquakes (Fig. 16b). The detailed visit of the structure after the two October events showed a worsening of the damage, mainly concentrated in the observed local mechanism. In any case the general crack pattern resulted to be substantially the same as reported during the first survey. No evidence of foundation settlements was observed after the three events.

6 Conclusions

The paper illustrates the behavior of school buildings affected by the recent seismic sequence that struck a vast area of Central Italy in the period August 2016 – January 2017. The analysis involves 1514 school buildings on which usability inspections were carried out after each event of the sequence. The inspections on school structures and the relevant analyses showed that:

- At the end of the seismic sequence, 65% of the school buildings resulted usable while 35% were unusable (i.e. 27% B/C and 8% E rating, respectively); in the category of unusable structures, RC resulted the most common structural type with damage mainly to non-structural members (i.e. B/C usability rating), while masonry was the most common structural type in the case of buildings with severe damage to structural members (i.e. E usability rating);

- At the end of the seismic sequence, the percentage of usable school buildings, among the inspected ones, goes from 68% for structures that experienced PGA lower than 0.1 g down to 14% for PGA greater than 0.30 g.
- According to the current seismic code provisions, the range of the design ground acceleration a_g (on stiff soil, horizontal surface) for school buildings, related to service and ultimate limit states in the regions struck by the earthquake sequence are: 0.025–0.100 and 0.035–0.125 g (service conditions, SLO and SLD, respectively), 0.065–0.300 and 0.075–0.380 g (ultimate conditions, SLV and SLC, respectively);
- Out of 1514 school structures, 802 resulted designed for gravity load only, corresponding to 53% of the dataset while 712 (i.e. 47%) were designed to sustain horizontal actions, but most of them according to obsolete seismic provisions;
- Although most of the buildings were not conforming to current seismic codes, however the behaviour of buildings designed to sustain horizontal actions was definitely better than those designed to sustain just gravity loads;
- According to the AeDES usability rating meaning, it is possible to assume as definitely satisfactory the behavior of buildings that even if experienced PGA values in the range of a_g currently adopted for the design of new constructions at ultimate limit states (SLV and SLC) resulted usable (A rating): 38 and 69% at SLV and 0 and 19% at SLC for gravity load and seismic load structures, respectively; by contrast, definitely unsatisfactory was the behavior of unusable buildings with E rating that experienced PGA values in the range of a_g currently adopted for the design of new constructions at service limit states (SLO and SLD): 9 and 5% at SLO and 4 and 0% at SLD for gravity load and seismic load structures, respectively;
- Considering the above percentages and that the “A” usability rating means no or very slight damage and the “E” usability rating means heavy damage but not collapse for almost all the buildings, the behavior of both gravity load designed and seismic load obsolete code designed buildings was however better than could be expected;
- The analysis of four case studies clearly shows that the damage level of the school buildings were clearly affected by plan and elevation structural regularity or irregularity, construction age and relevant code provisions, number of storeys, pre-existing damage, construction quality, and previous strengthening interventions.

This study gives preliminary but significant information on the seismic behavior of school buildings under the recent seismic sequence recorded in Central Italy. It can help to set up suitable retrofit programs to improve seismic safety of school buildings, with a special concern to the limitation of the damage to non-structural members, which makes buildings unusable and thus strongly impacts on the school function recovery time.

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