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The contribution of ReLUIS to the usability assessment of school buildings following the 2016 central Italy earthquake

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ABSTRACT Recent earthquakes have shown the key role of post-earthquake technical inspections aimed at assessing the seismic safety and/or usability of buildings and the functionality of infrastructural systems, in order to minimize the impact of losses on citizens as fast as possible. The AeDES form is used to evaluate the safety conditions of buildings in order to enable people to return to their social and economic activities. The ReLUIS consortium has been heavily involved in the post-earthquake emergency phase of the central Italy earthquake. Consortium support to the Department of Civil Protection consisted of technical surveys of public buildings, with emphasis on school buildings, hospitals, strategic infrastructures, and sites with historical and monumental significance. Researchers from several Italian universities carried out *in situ* surveys in order to reduce social hardship. Usability and damage assessment was carried out by teams of surveyors made up of experts from a list of ReLUIS researchers mobilized in accordance with emergency procedures in case of earthquake. The potential vulnerabilities of several case studies involving school complexes are discussed, and recommendations for further investigations are provided.

Key words: ReLUIS, central Italy earthquakes, usability and damage assessment, school buildings.

1. Introduction

One of the main objectives of the Department of Civil Protection (DPC) in the aftermath of an earthquake is the assessment of damage on strategic buildings and the definition of a sound strategy to quickly repair and strengthen the ones with minor structural damage only. The AeDES form (Baggio *et al.*, 2007a, 2007b) is the tool to evaluate the safety conditions of buildings in order to enable people to return to their social and economic activities. The form is a first-step survey form for post-earthquake damage and usability assessment; it defines the usability of the building based on the visual *in situ* inspection. On May 5, 2011, the AeDES form, together with its field manual, became Italy's official tool to assess ordinary buildings damaged by an earthquake (D.P.C.M., 2011). Since the L'Aquila 2009 earthquake, the inter-university consortium ReLUIS (i.e., University Seismic Engineering Laboratories Network) has provided strong support to DPC for performing technical surveys of public buildings.

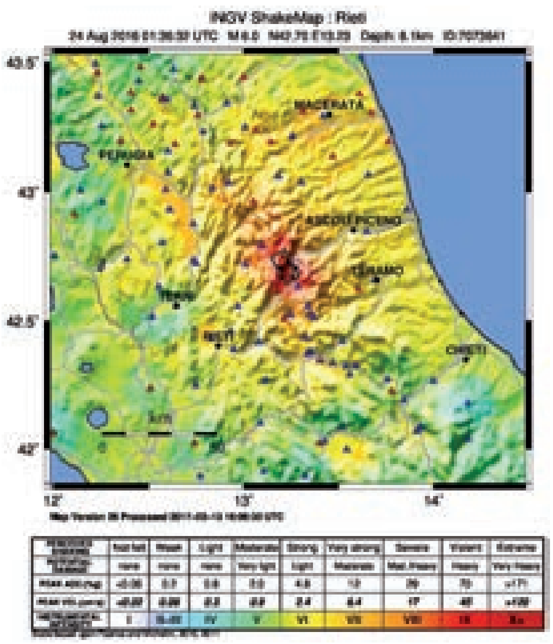
The ReLUIS consortium was born with a conventional act signed on April 17, 2003, like similar organizations in the United States (i.e., the Network for Earthquake Engineering Simulation - NEES) and in Asian countries (i.e., ANCER). The consortium, which is a Competence Centre of the DPC, has been strongly involved in the post-earthquake emergency phase of recent Italian earthquakes. In particular, researchers from several Italian universities were involved in assessing damage and usability of public structures, with emphasis on school buildings, hospitals, strategic infrastructure, and sites with historical and monumental significance. The researchers were mobilized in accordance with earthquake emergency procedures in the aftermath of the 2009 L'Aquila, 2012 Emilia, and 2016 central Italy earthquakes (Dolce *et al.*, 2009, 2016; Di Ludovico *et al.*, 2012, 2017a, 2017b; Frascadore *et al.*, 2015).

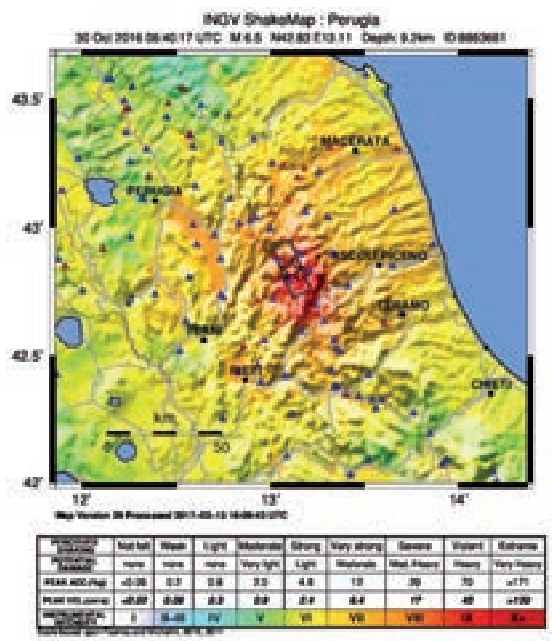
The recent central Italy earthquake consisted of a sequence of events. The first earthquake of the sequence (M=6.0) hit several central Italy regions (i.e., Abruzzo, Lazio, Umbria, Marche regions) on August 24, 2016, at 01:36:32 GMT; the quake epicentre was close to Amatrice, Accumoli, and Arquata del Tronto and caused diffuse building collapse and about 300 casualties. Two months later, on October 26, 2016, two events, M=5.4 (17:10:36 UTC) and M=5.9 (19:18:06 UTC), extended the seismogenic volume to the NW. Four days later, on October 30, 2016, at 06:40:18 UTC, an event of M=6.5, struck the area corresponding to the Sibillini mountains, with epicentre located close to Norcia, Umbria region. The quakes that occurred after the first event caused extensive damage, especially to many historical buildings, but no deaths were registered.

2. *In situ* inspections of school buildings in the aftermath of the central Italy earthquakes

In the post-earthquake emergency phase of the recent central Italy earthquake, which occurred on August 24, 2016, at 03:36 AM local time, the total number of surveys carried out by technicians of several institutions involved 874 school structures in four regions of central Italy (see Fig. 1). In particular, 203 school structures were inspected in the Abruzzo region, 144 school structures throughout the Lazio region, 443 and 84 school structures in the regions of Marche and Umbria, respectively. In terms of usability assessment according to the AeDES form classification, 661

Fig. 1 - Location of regions involved (in red) in the central Italy earthquake and MCS instrumental intensity shake maps of the two main shocks of the sequence: M=6.0 August 24, 2016 (left) and M=6.5 October 30, 2016 (right).





school structures, corresponding to 76% of the data set, were assessed at usability rating A (i.e., usable building, no significant damage). The remaining school structures were found to be usable after short-term countermeasures or partially usable, usability rating B or C (i.e., 164 structures with limited or no structural damage but with severe non-structural damage, about 18% of the data set), or unusable, E rating (i.e., 49 structures with high structural or non-structural risk, high external or geotechnical risk, about 6% of the data set).

In the aftermath of the October 2016 seismic events (M=5.9 and M=6.5), school inspections were carried out on a total of 1,015 structures, which includes some of the school structures reviewed after the August event. In particular, 223 school structures in the Abruzzo region, 140 school structures all over the Lazio region, 454 and 198 school structures in the regions of Marche and Umbria, respectively. In terms of usability assessment, about 61% of the school structures were assessed with usability rating A (625 buildings), about 32% B/C (322 structures), and about 7% E (68 structures). Thus, after the events of October 2016, the extent and severity of damage detected on school buildings significantly increased: the total percentage of unusable school structures (B/C or E usability rating) increased from 24% up to 39%.

2.1. ReLUIS activities in the aftermath of the August 24, 2016 earthquake

The work of the ReLUIS consortium started on August 29, 2016, under the supervision of DPC at DiComaC (Direction of Command and Control), located in Rieti, Italy. The usability assessment of school and public buildings was carried out from August 29 to September 21 in an area near the borders of the Umbria, Lazio, Abruzzo, and Marche regions. This involved surveys on 160 school complexes (i.e., one or more school structures consisting of joined buildings or school sports facilities) for a total of 253 school structures, and 47 public buildings for a total of 54 structures. The number of school structures inspected in each region is depicted in Fig. 2a. In terms of usability assessment (Fig. 2b), about 73% of the school structures were assessed with usability rating A (184 structures with no significant damage), about 19% B/C (48 structures with no significant damage on structural members) and about 8% E (21 structures with significant damage on both structural and non-structural elements).

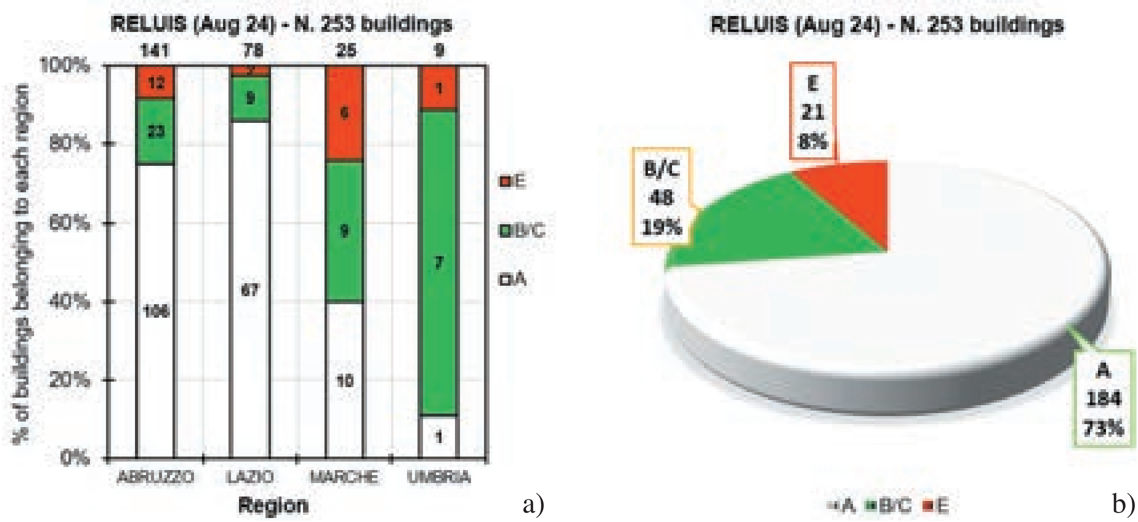
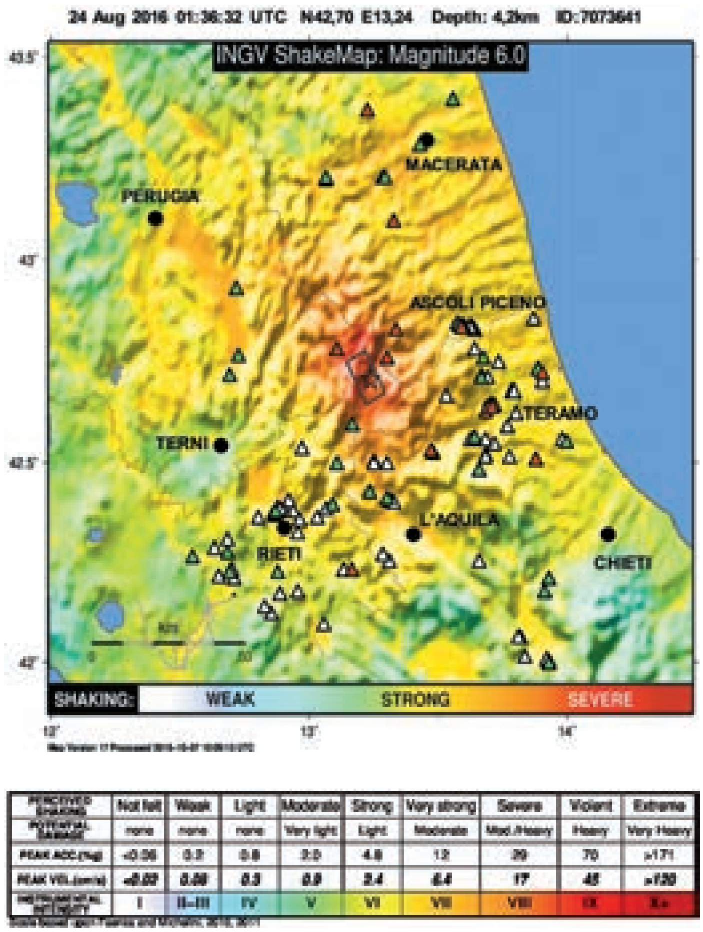


Fig. 2 - Surveys on school buildings after August 24 shock: a) number of buildings investigated in each region; b) usability rating.

Fig. 3 shows the location of surveyed school buildings on the Mercalli-Cancani-Sieberg (MCS) instrumental intensity shake map (http://shake map.rm.ingv.it/) of the M=6.0 August 24, 2016 shock (Fig. 3a) and the distribution of the heavily damaged school buildings (usability rating E) related to each class of peak ground acceleration (PGA) (Fig. 3b). School buildings were mostly located in sites characterized by a PGA of less than 0.15 g (corresponding to light or



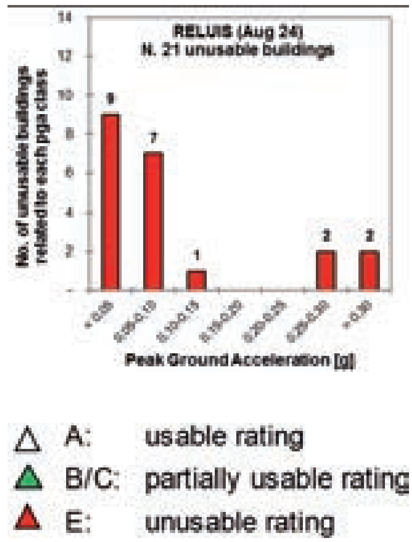


Fig. 3 - Location of surveyed school structures on the MCS instrumental intensity shake map for the M=6.0 August 24 shock.

moderate potential damage), whereas only a small percentage were in sites with PGA greater than 0.25 g (heavy potential damage). From the data collected on the AeDES forms, it was possible to observe that most of the above-mentioned structures characterized by significant damage suffered that damage to non-structural elements, with only slight damage to structural elements. The extent of the non-structural damage was the main reason they were deemed unusable. By contrast, only a small percentage of school buildings, which were located in areas affected by PGA greater than 0.25 g, suffered major damage to both non-structural and structural members.

2.2. ReLUIS activities in the aftermath of the October 26 and 30, 2016, earthquakes

On-site inspections of schools and public buildings were carried out from November 3 to November 28. They involved surveys of 122 school complexes, for a total of 221 structures, and 82 public buildings. This included 26 school complexes, for a total of 57 structures, were inspected in the Abruzzo region; 96 school complexes, for a total of 163 structures, throughout the Marche region; and one school building in Umbria (see Fig. 4a). The total percentage of unusable school buildings (B/C or E usability rating) increased, with respect to the August 24 earthquake, to 24% of buildings with usability rating B/C, and 10% of buildings with usability rating E (see Fig. 4b).

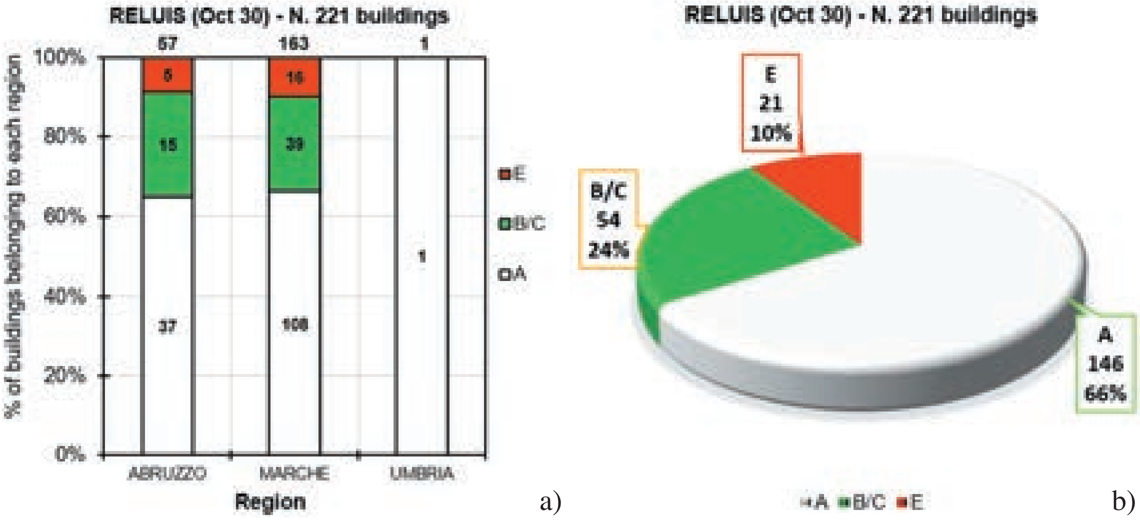
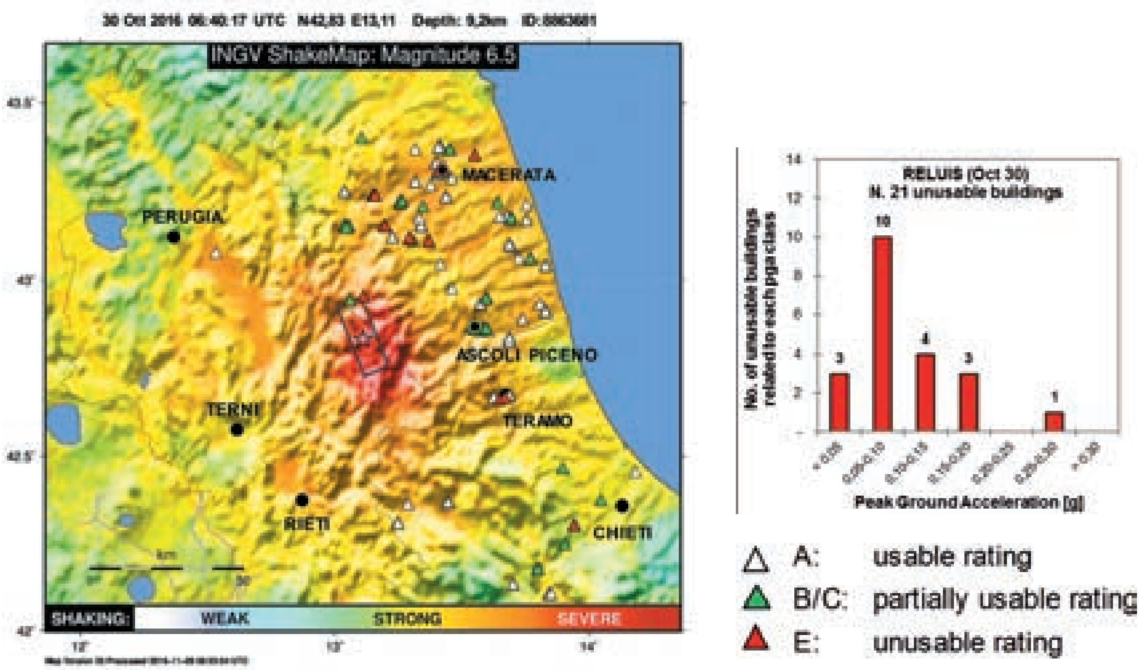


Fig. 4 - Surveys on school buildings after October 30 shock: a) number of buildings investigated in each region; b) usability rating.

Fig. 5 shows the location of surveyed school buildings on the MCS instrumental intensity shake map of the *M*=6.5 October 30, 2016, shock (Fig. 5a) and the distribution of the heavily damaged school buildings (usability rating E) related to each PGA class (Fig. 5b).



PERCEIVED SHAKING	Not felt	Weak	Light	Moderate	Strong	Very strong	Severe	Violent	Extreme
POTENTIAL DAMAGE	none	none	none	Very light	Light	Moderate	Mod./Heavy	Heavy	Very Heavy
PEAK ACC.(%g)	<0.05	0.3	0.8	2.0	4.8	12	29	70	>171
PEAK VEL.(cm/s)	<0.02	0.08	0.3	0.9	2.4	6.4	17	45	>120
INSTRUMENTAL INTENSITY	I	II-III	IV	V	VI	VII	VIII	IX	X+

Fig. 5 - Location of surveyed school structures on the MCS instrumental intensity shake map for the *M*=6.5 October 30 shock.

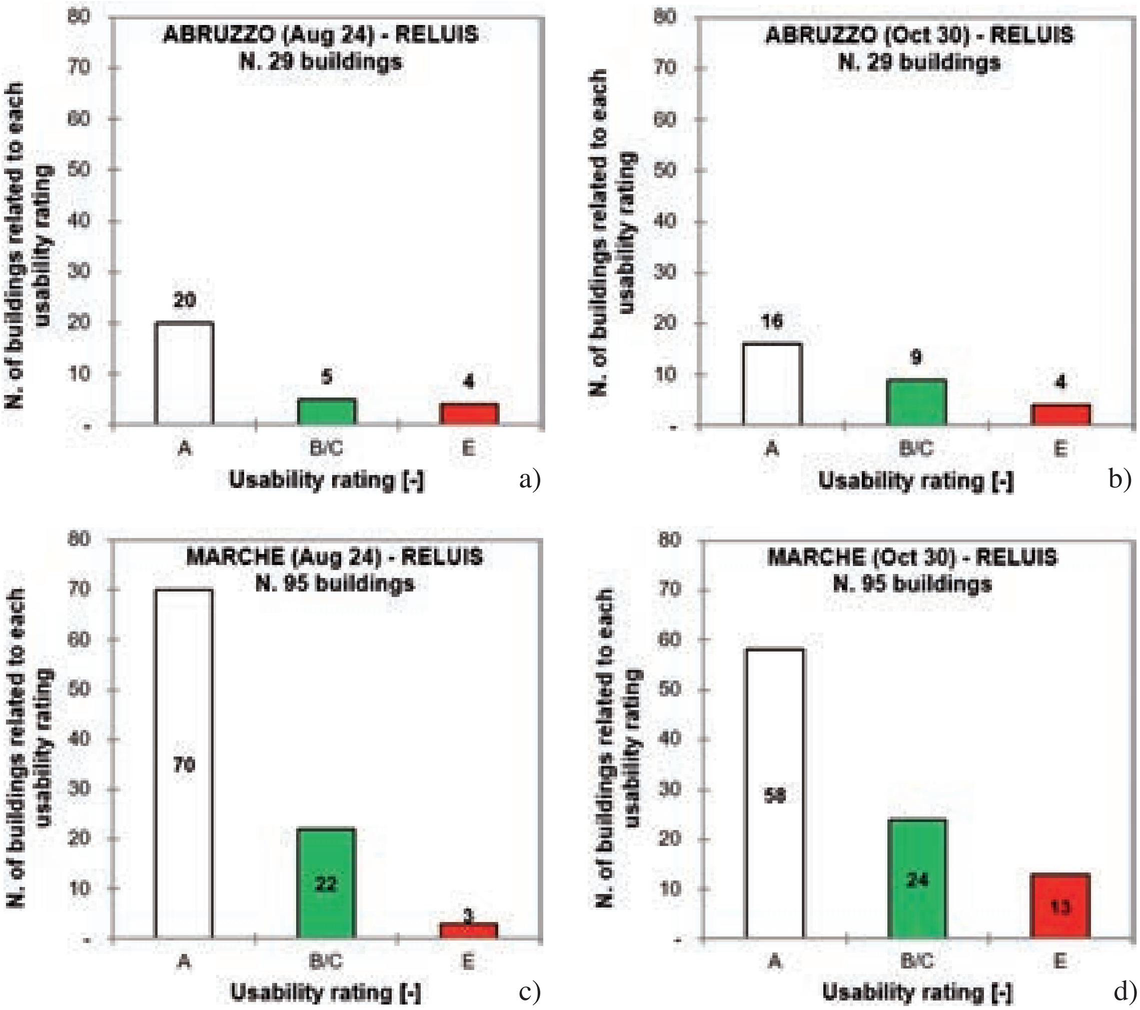


Fig. 6 - Usability rating comparison of school structures inspected in the aftermath of August and October 2016 earthquakes: a) and b) Abruzzo region; c) and d) Marche region.

Fig. 6 compares the usability rating of school buildings inspected in the Abruzzo region (29 school structures) and all over the Marche region (95 school structures) in the aftermath of August 24 and the October 30, 2016 earthquakes. Following the October seismic events, there was a significant increase in damaged structures both in the Abruzzo and the Marche regions:

- damage on non-structural members increased especially in buildings located in Abruzzo (B/C usability rating increase of about 14%);
- damage to structural members rose significantly in the Marche region (11% of the data set), while there was no percentage change in Abruzzo.

3. Damage to school buildings in the aftermath of the central Italy earthquakes

After the earthquakes of August 24 and October 30, 2016, ReLUIS technicians carried out surveys on a total of 282 school complexes. A representative set of results, for a sample size of

Table 1 - Damage to 14 school complexes in the aftermath of the 2016 central Italy earthquakes.

ID	Struc. type	School Complex	Municipality	Region	PGA [g]		MCS		Usability rating	Previous Seismic Retrofit		Non-structural damage	Structural damage	Remarks
					Aug 24	Oct 30	Aug 24	Oct 30						
1	RC buildings	*Einstein*	Teramo	Abruzzo	0.05	0.08	V	VI	A	-	-	Slight cracks on some internal partitions	-	-
2		*Cotugno*	L'Aquila	Abruzzo	0.05	0.05	V	V	A	2009	Local strengthening on several internal partitions	Slight cracks on some internal partitions	–	–
3		*Ciancarelli*	Rieti	Lazio	0.04	0.08	V	VI	A	2014-2015	Beam-column joints reinforced with CFRP; Short RC columns were added at the base of the pre-existing ones of the gym	Cracking at the interface between old and new concrete of columns; Slight cracks on some internal partitions	-	-
4		*O. Licini*	Ascoli Piceno	Marche	0.07	0.11	VI	VII	B-C	-	-	Diffuse diagonal and sub-horizontal cracks on internal partitions	-	Lacking in providing proper lateral-resisting systems in both directions for strong in-height irregular building
5		*R. Battaglia*	Norcia	Umbria	0.37	0.48	VIII	VIII	B-C	-	-	Diagonal and some sub-horizontal cracks in non-structural masonry infills	-	-
6		*Hotel Management*	Amatrice	Lazio	0.45	0.39	VIII	VIII	E	-	-	Collapse of several partition walls and ceilings; Cracking of external masonry infills	Very shear cracks on exterior beams; Severe damage to the stairwell	-
7		*Pascal*	Teramo	Abruzzo	0.07	0.09	VI	VI	E	-	-	Out-of-plane behaviour of infill walls; Cracks on non-structural masonry infills	Damage to structural joints with seismic pounding effect between buildings	Insufficient technical joints; very irregular in-plane configuration
8		*Mons. Paoletti*	Pieve Torina	Marche	0.11	0.18	VII	VII	E	-	–	Strong and diffuse damage to both internal and external masonry partitions and out-of-plane phenomena of external infill walls	Horizontal, vertical and diagonal cracks on structural elements	Building designed only for gravity loads, e.g. one-way frames
9	Masonry buildings	*E. Ricciardi*	Sarnano	Marche	0.07	0.11	VI	VI	A	after 1997	Connectors added at the roof level to restrain the out of plane of the walls	Slight diagonal cracks in non-structural internal partitions and spandrels	–	–
10		*G. Milli*	Teramo	Abruzzo	0.05	0.07	V	VI	B-C	2009	Travertine plates partially debonded after the 2009 L'Aquila earthquake and retrofitted with connectors	Debonding of travertine plates; Collapse of the plaster cover of the window lintel	–	–
11		*B. Tacchi*	Acquasanta Terme	Marche	0.24	0.28	VIII	VIII	E	-	-	Diagonal and some sub-horizontal cracks in non-structural partition walls	Significant shear cracks on the vertical load bearing elements; Cracks between floors and masonry bearing walls	Interaction between the masonry piers and the RC slabs
12		*Don Bosco*	Falerone	Marche	0.08	0.08	VI	VI	E	-	–	Plaster expulsion with damage to frontier elements	False vault collapse; Triggering of the façade overturning mechanism and shortening of the organ	-
13		*G. W. Bruni*	Montegallo	Marche	0.28	0.34	VIII	VIII	E	2004	Some new transversal walls, made by Poroton® bricks were added	Cracking of some infill walls	Shear cracks on external bearing walls	-
14		*Pievebovigliana School*	Pievebovigliana	Marche	0.08	0.16	VI	VII	E	after 2007	A planar frame made by welded steel beams running in orthogonal directions added at the ceiling level to restrain the possible out of plane of the walls	Failure of the inner non-structural brick layer; Dislocation of the bricks of the structural masonry walls	Shear failure of the inner and outer masonry walls, causing important X-shaped cracks (>1cm)	Severe torsional effects for very irregular in-plane configuration

14 school complexes, is presented in Table 1: 7 school complexes in the Marche, 4 in Abruzzo, 2 in Lazio, and 1 in Umbria. The table also reports the structural type of buildings, the location, the usability rating, the MCS and the PGA of the two main shocks of the sequence, M=6.0 August 24 and M=6.5 October 30, the description of previous seismic retrofitting, the non-structural and the structural observed damage, and general remarks.

A detailed discussion of the damage to structural and/or non-structural elements is reported in detail in the next paragraphs.

3.1. Usable school buildings

This section focuses on the description of the seismic behaviour of four school complexes: Einstein high school in Teramo (Abruzzo); Cotugno high school in L'Aquila (Abruzzo); Ciancarelli high school in Rieti (Lazio); and E. Ricciardi elementary school in Sarnano (Marche). The 4 school complexes suffered only minor damage, entailing no school closure after the earthquakes.

The **Einstein high school** is located in Teramo city (Abruzzo), which was marginally affected by the August 24 event, with a PGA of 0.05 g. The school complex hosts about 700 students and teachers; it consists of six 3-storey RC buildings (Fig. 7a) from different construction periods. Two buildings, the oldest ones, were built in the 1960s, when Teramo was not seismically classified, and show the typical characteristics of the gravity load-designed RC buildings of that period, e.g., one-way frames. Other buildings were built in the 1970s, and construction ended after 1984, the year of the first seismic classification of Teramo.

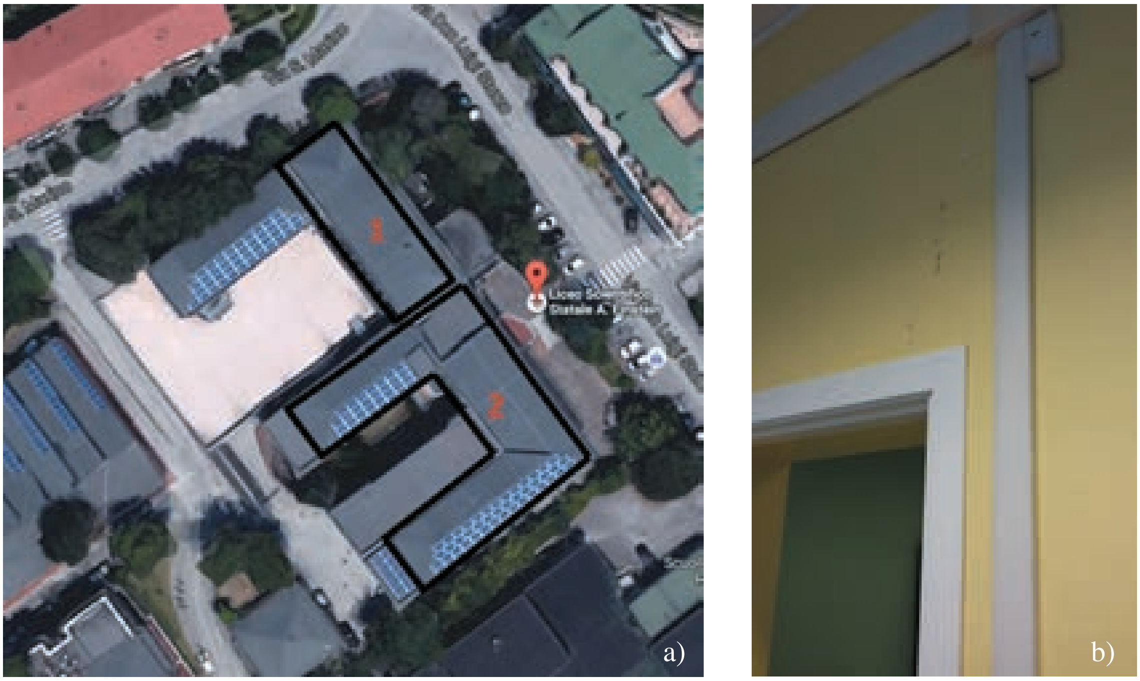


Fig. 7 - Einstein high school building: a) map view of the complex (No. 1 and No. 2 buildings are the oldest buildings); b) slight damage detected during the September 12, 2016 survey.

Visual inspection of the buildings showed no structural damage, while slight damage was found only in some internal partitions (Fig. 7b). Specifically, the detected damage to the partitions was null in the most recent buildings, and D1 (slight damage) with an extension of less than 1/3 in the older ones, according to AeDES form definitions (Baggio *et al.*, 2007a, 2007b).

Local technicians of Teramo Province provided additional information and technical documentation. Particularly interesting were the results of the seismic vulnerability assessment previously performed on the two oldest buildings. The assessment was performed according to the current Italian technical code (NTC, 2008), adopting the non-linear static analysis method and assuming a normal knowledge level (KL2). Based on some destructive and non-destructive *in situ* tests, a mean compressive strength f_{cm}=12.5 MPa was assigned to concrete, and a mean yielding strength f_{ym}=317 MPa was assigned to steel. The concrete strength appears lower than the typical mean values expected for that period (Masi *et al.*, 2014).

The structures are built on ground type C. The analysis results, in terms of capacity/demand ratio related to the life safety limit state, show very low values, in the range of 0.04-0.06 (i.e., 4%-6% of the seismic safety index with respect to new building standards), corresponding to capacity values in terms of ground acceleration, $a_{g,C}$, in the range 0.012-0.017 g.

Considering the rules adopted in the usability surveys relating the usability outcome to the detected damage level, the buildings were assessed usable (A rating outcome according to AeDES classification). However, the very low seismic capacity values given in the vulnerability assessments were mentioned in the notes of the AeDES form.

To make a comparison with the results of the vulnerability assessment, it is worth analysing the records made available by the Italian Accelerometric Network (RAN), managed by the Italian

DPC, for the *M*=6.0 August 24 event. These records show a_g values in Teramo of up to 0.06 g (ground type A), then higher a_g values can be expected at the school site (ground type C), up to 0.08-0.09 g. Therefore, recorded a_g values appear far higher than the computed capacity for the limit state (i.e., up to 5-6 times higher). However, no structural damage was found in the surveyed buildings (Masi *et al.*, 2016).

The **Cotugno high school** complex, located to the west of L'Aquila city, hosts one of the schools with the largest number of students in the municipality. The student population at the time of the quake was about 1,200, plus the faculty and support staff, for a total of more than 1,400 people.

The complex (Fig. 8a) consists of eight buildings, built between 1988 and 1994. At the time of their design, the territory in which the city of L'Aquila is located was classified as medium seismicity (Zone 2 on a scale from 1 to 3).

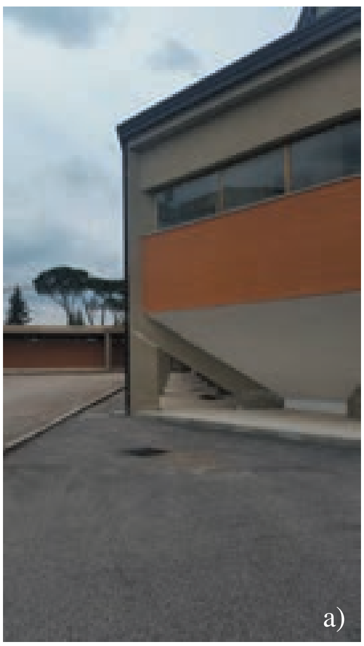
Fig. 8 - Cotugno high school building: a) plan view of the complex; b) and c) one of the damaged partitions after October 30, 2016 earthquake, plaster reinforcement mesh installed in 2009 is visible.

Following the earthquake of magnitude *M*=6.3 that struck the city April 6, 2009 (epicentre about 5 km away from the school), 6 buildings were classified as slightly damaged (B usability rating), with damage of infills, but no structural damage. The remaining 2 buildings, the gymnasium and the multipurpose rooms, were declared usable. Immediately after the earthquake, damaged partitions and infills were repaired or rebuilt, and in the meantime limited structural reinforcement, classified as "local intervention" by Italian technical code (§ 8.4.3 in NTC, 2008), was carried out on the structural elements of some buildings (Del Vecchio *et al*., 2014, 2016; Frascadore *et al*., 2015; Dolce *et al*., 2016). Most of the complex structures returned to use in June 2009, and temporarily hosted provincial administration offices; months later, they were used again as school buildings.

After the October 30, 2016 earthquake, during a field survey, slight damage was found on four partitions, illustrated in Fig. 8b. The plaster reinforcement grid installed on the partition in 2009 is visible in Fig. 8c. The school complex was declared usable, and re-opened once the minor damage was repaired.

It is worth noting that the provincial administration of L'Aquila commissioned an assessment of the seismic vulnerability of the entire complex in 2013. Starting from the results of a large laboratory and field testing of the structure with particularly conservative values for the resistance of materials adopted in the structural analysis, most of the buildings were deemed unable to lead vertical loads. The seismic safety index was set at zero.

The **Ciancarelli high school** is located in Rieti (Lazio region). It consists of two main buildings, one for classrooms and offices, comprising three floors, and one for the gymnasium and the seminar room (one 10-m-high floor). Both of the buildings have a RC frame structure with RC walls only at the stairs. The school was built at the end of the 1970s. Seismic retrofitting was undertaken in 2014-2015, consisting of the reinforcement of the beam-to-column joints with externally bonded carbon fibre reinforced polymer (CFRP) and the modification of the RC elements of the gymnasium. Short columns were added at the base of the pre-existing ones, whose lower portion was originally designed as a short-span oblique cantilever (Fig. 9a).


a)


b)

Fig. 9 - Ciancarelli high school building: a) RC columns of the gymnasium originally designed (end of 1970s) as short-span oblique cantilevers and modified by the addition of the vertical lower column during recent (2014-2015) seismic retrofitting; b) small cracks at the structural joint.

The building showed very limited damage after the August 24, 2016 earthquake. The seismic action recorded in Rieti, 44 km from the epicentre, was 0.06 g in terms of PGA. More specifically, during a survey on September 5, 2016, no significant damage was observed on the structural elements (frame structures, beam-column joints, roof, stairs), nor on the perimeter infill walls. The only exception was the separation between the original RC columns of the gymnasium and the new columns added below. A crack developed at the interface between old and new concrete, indicating a lack of or at least insufficient connection. Cracks were also observed on some internal partitions, especially near the structural joints, due to the movement between the portions of the structure (Fig. 9b). The school complex was declared usable.

The **E. Ricciardi elementary school** is located in Sarnano (Marche region). The three-storey masonry building was built in 1950, and it is regular in elevation (Fig. 10a). The vertical elements are mainly made of unreinforced brickwork with RC slabs. Seismic retrofitting was undertaken after the 1997 central Italy earthquake, that consisted of adding connectors in orthogonal directions at the roof level to restrain any walls that were possibly out of plane (Fig. 10b).

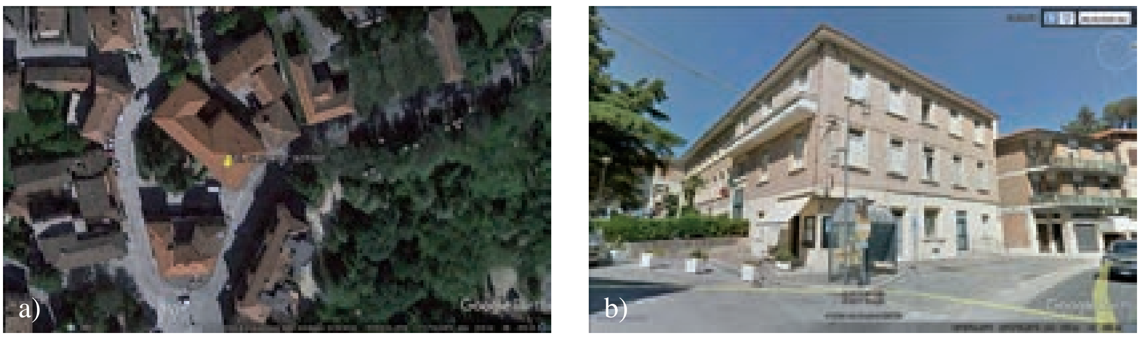


Fig. 10 - E. Ricciardi elementary school building: a) plan view of the school; b) external view of the building where the connectors installed after the 1997 central Italy earthquake are visible.

The building showed very limited damage after the *M*=5.9 October 26, 2016 earthquake. More specifically, during the survey of October 28, 2016, no significant damage was observed on the structural elements, only slight diagonal cracks to some internal partitions and the spandrels of the central longitudinal walls. A crack developed at the interface between the masonry walls and the roof, indicating a lack or at least insufficient transverse connection. The closer inspection after the *M*=6.5 October 30 event showed a general worsening of the damage level, both in terms of crack enlargements and detachment. Overall, however, the crack pattern was determined to be substantially the same as reported during the first survey. The school complex was declared usable.

3.2. Unusable slightly damaged school buildings

This section focuses on school buildings assessed as unusable due to slight damage to structural components or to extensive damage to non-structural ones, B or C usability rating according to the AeDES form. Specifically, this was the damage pattern detected on three school complexes: G. Milli high school in Teramo (Abruzzo), O. Licini high School in Ascoli Piceno (Marche), and R. Battaglia high school in Norcia (Umbria).

Fig. 11 - G. Milli high school building: a) external view of the complex; b) detachment of a travertine plate; c) detail of the collapsed plaster cover of the window lintel.

The **G. Milli high school** of Teramo (Abruzzo), currently used as a foreign languages, economics, and social sciences high school, was built in 1934-1938. The building has a rectangular layout, with a central courtyard where a lecture hall, which is part of the main building, is located. On one side of the building is the main entrance, and on the opposite side is the gymnasium. The building has three storeys above ground and a basement. The vertical structures are mainly made of unreinforced brickwork, with some RC columns within the walls of the lecture hall and the gymnasium. RC is also used for floors and staircases. The sloped roof, supported by timber trusses, was added in 1952 above the original horizontal plane roof.

The school was inspected in the aftermath of the August 24 event and, despite a maximum PGA as low as 0.066 g, the main building was tagged as temporarily unusable and the lecture hall was tagged as unusable. Whereas the latter construction was affected by severe pre-existing damage to the roof, the main building was assessed temporarily unusable because of damage to non-structural elements. As a matter of fact, the main elevation shows a travertine stone cladding (Fig. 11a), and due to ground shaking, some plates detached from the back wall (Fig. 11b), precluding walking in the area below. The plates are connected to the load-bearing walls with mortar, but in a few cases, one or two metal ties per plate were observed. These ties were installed after the 2009 L'Aquila earthquake, which already highlighted the vulnerability of the façade.

More significant non-structural damage occurred within the building. In about ten classrooms a 40-60 mm-thick plaster cover of the window lintel cracked, and in some cases collapsed (Fig. 11c). The significant weight of such stucco finishing, usually loosely connected to clay brick fragments in order to obtain the desired thickness, posed a hazard to students. The observed behaviour confirms the relevance of the performance of non-structural elements in the overall response of the building (Lagorio, 1990), which becomes critical if the building is a school with large population exposure and a possible role as a meeting place or shelter in the emergency management phase.

The **O. Licini high school** is located in Ascoli Piceno (Marche), at a distance of about 30 km from the epicentre of the August 24 central Italy earthquake. The PGA which hit the building was estimated to be lower than 0.10 g.

The five-storey building was built in the 1970s and underwent strengthening interventions in the upper storeys in the late 1990s. It is characterized by an average floor plan of about 1400 m^2. Inter-storey height is variable: it is larger than 5 m in the three lower storeys and around 3.5 m in the two upper storeys. Slender columns at the lower levels, together with huge mass lumped at the upper levels, lead to a significant irregular vertical configuration (Fig. 12a).

The structural system is composed of a series of RC transverse planar frames which are connected only by non-structural masonry infills along the longitudinal direction (Fig. 12b). The complete absence of an adequate structural lateral-resisting system along the longitudinal direction forced these stiff infills to act as bracing systems during the earthquake, but they were not strong enough. Thus, diffuse damage like typical diagonal and sub-horizontal cracks were observed on internal partitions at each storey during the survey. This was the result of the conceptual design of the original project, which was lacking in proper lateral-resisting systems in both directions.

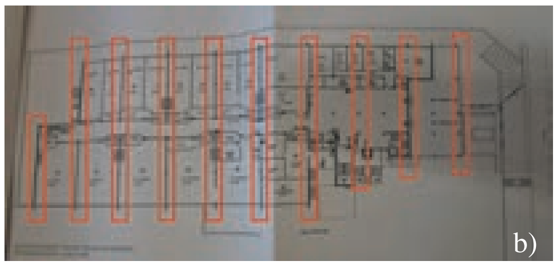


Fig. 12 - O. Licini high school building: a) external view of the building; b) plan of an intermediate floor with the RC (transverse planar frames in red boxes).

The **R. Battaglia high school** complex is located in Norcia (Umbria**)**. The recorded PGA in Norcia after the event of August 24 reached 0.37 g (recorded by the NRC seismic station, part of the RAN-DPC network). The complex is a high school with an average of 100 occupants and it consists of two joined buildings.

The first and oldest building has RC walls, built between 1982 and 1986; the structure has three storeys and a basement, and it is regular in plan and elevation. In this building, damage on some infill walls and plaster detachment was observed.

The second building is a RC frame building, built between 1997 and 2001. Inspection showed detachment from the frame of the external infills of the western façade both at the first and second floor (Fig. 13a), probably due to the poor connection between structural and non-structural elements. Diffuse damage like the typical diagonal and sub-horizontal cracks was also observed, with fall of some hollow bricks (Fig. 13b). The usability rating was B for both buildings.

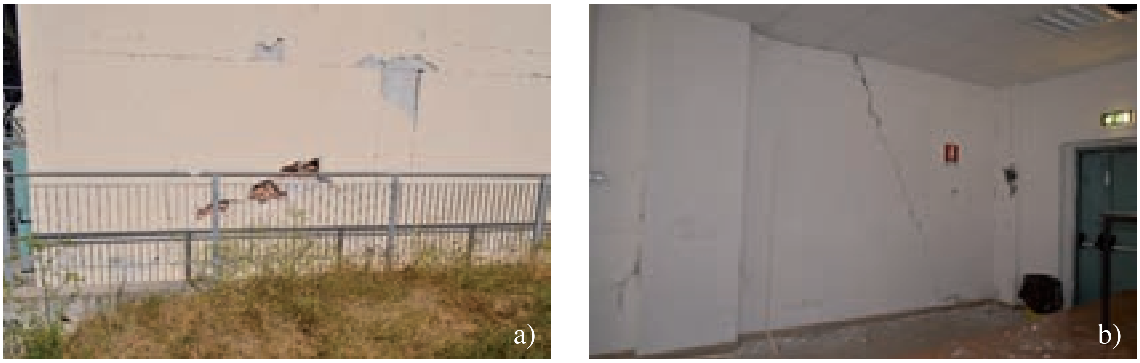


Fig. 13 - R. Battaglia RC frame building: a) poor connection between structural and non-structural elements; b) diagonal and some sub-horizontal cracks in non-structural masonry infills.

3.3. Unusable heavily damaged buildings

This section focuses on buildings unusable due to heavy damage to both structural and non-structural components, E usability rating according to the AeDES form. Specifically, this is the damage pattern detected on seven complexes (three RC and four masonry structures), namely: the Hotel Management school in Amatrice (Lazio); Pascal high school in Teramo (Abruzzo); Mons. Paoletti elementary school in Pieve Torina (Marche); B. Tucci primary school in Acquasanta Terme (Marche); Don Bosco high school in Falerone (Marche); G. M. Rizzi primary school in Montegallo, Balzo (Marche); and the elementary school of Pievebovigliana (Marche).

The **Hotel Management school** is one of the tallest buildings in Amatrice (Lazio), one of the most damaged municipalities in the August 24 earthquake. The school complex was built in the 1980s and hosted nearly 100 students. The structure, which has six floors, consists of RC frames that, on the outside, are infilled with clay masonry (Fig. 14a). Because the building is under criminal investigation, the inspection was carried out from the outside on October 3, 2016. Several aftershocks and earthquakes struck the building after this date, but the building has not collapsed. Inspection showed the collapse of several partition walls and ceilings, and cracking of the external walls. Furthermore, some external beams show tiny shear cracks. From the outside, it was possible to observe severe damage to the stairwell, with buckling of the RC ramp (Fig. 14b).

Fig. 14 - The Hotel Management school of Amatrice: a) external view of the building; b) collapse in the hall and damage of RC stairs.

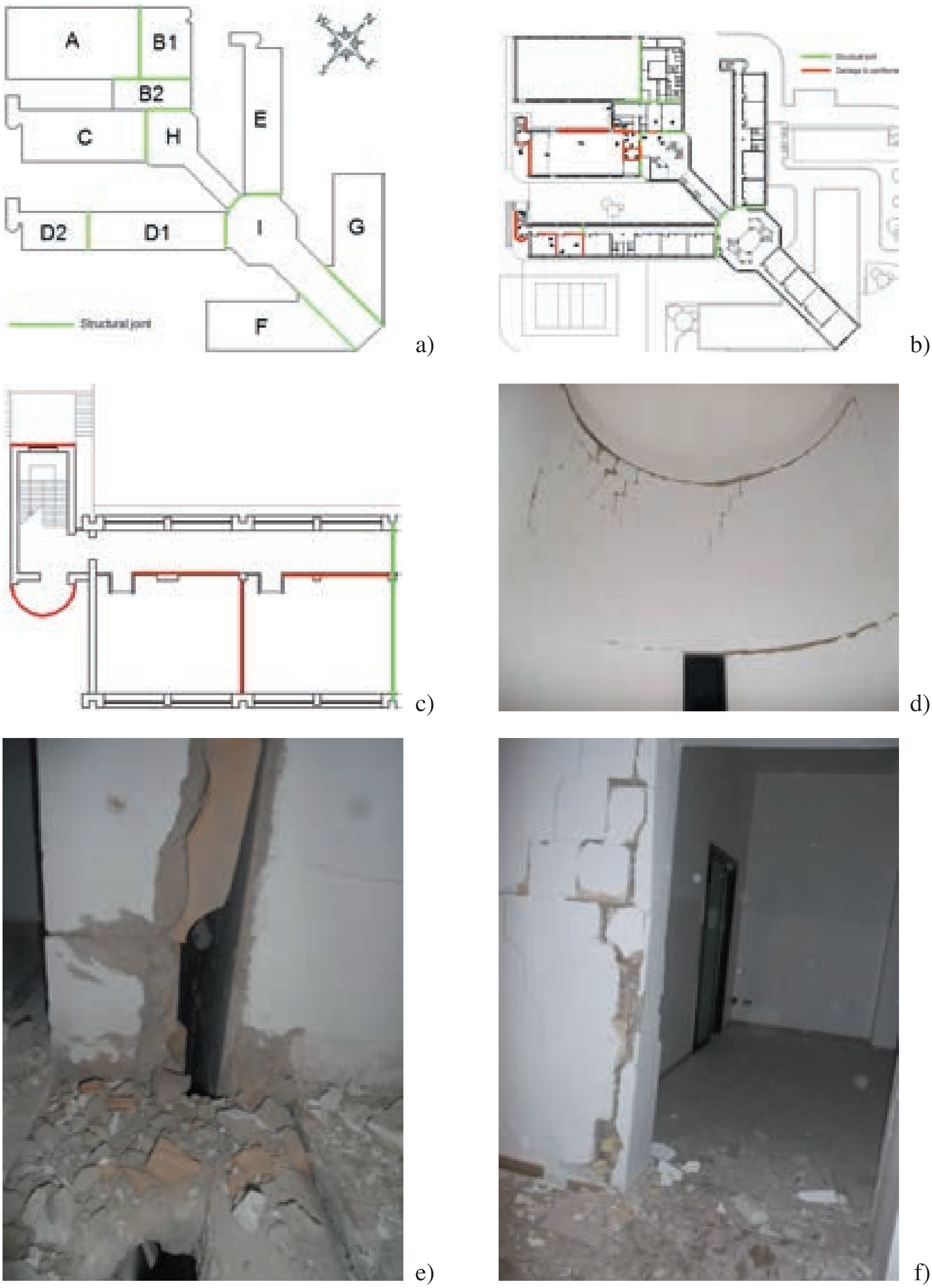


Fig. 15 - Pascal high school building: a) plan view of the complex and structural joints (green lines); b) location of the most significant damage (red line) in buildings D2, C, H, B2; c) and d) building D2 original project with eccentric damaged stairwell; e) damage to structural joint between buildings B2 and C; f) damage to non-structural masonry infills between buildings B2, C, and H.

The **Pascal high school** of Teramo (Abruzzo) is a RC structure with infill masonry walls, built in the 1990s. This school is regularly attended by 700 students and its area is about 9700 m^2. The construction consists of eleven discrete structures divided by technical joints with a gap of about 7-10 cm (Fig. 15a). After the shock of August 24, the first survey was conducted on September 1, 2016 and damage was mainly found in buildings D2, C, H, and B2, as shown in Fig. 15b.

In building D2, damage was detected in the stairwell, which appeared out of plane (Figs. 15c and 15d). Out-of-plane behaviour of the infill walls was observed, with the risk of collapsing (Fig. 15d). For this reason, the area around the stairwell was declared off-limits.

Buildings B2, C, and H also show damage on infill walls due to insufficient structural joint (Figs. 15e and 15f), with a seismic pounding among buildings. After the shock of October 30, the dimension of the crack pattern significantly increased.

The **Mons. Paoletti elementary school** is a three-storey building located in Pieve Torina (Marche). According to its original documentation and on-site inspection, it is regular in plane and elevation with an area of about 680 m^2 (for each level). The building is characterized by a

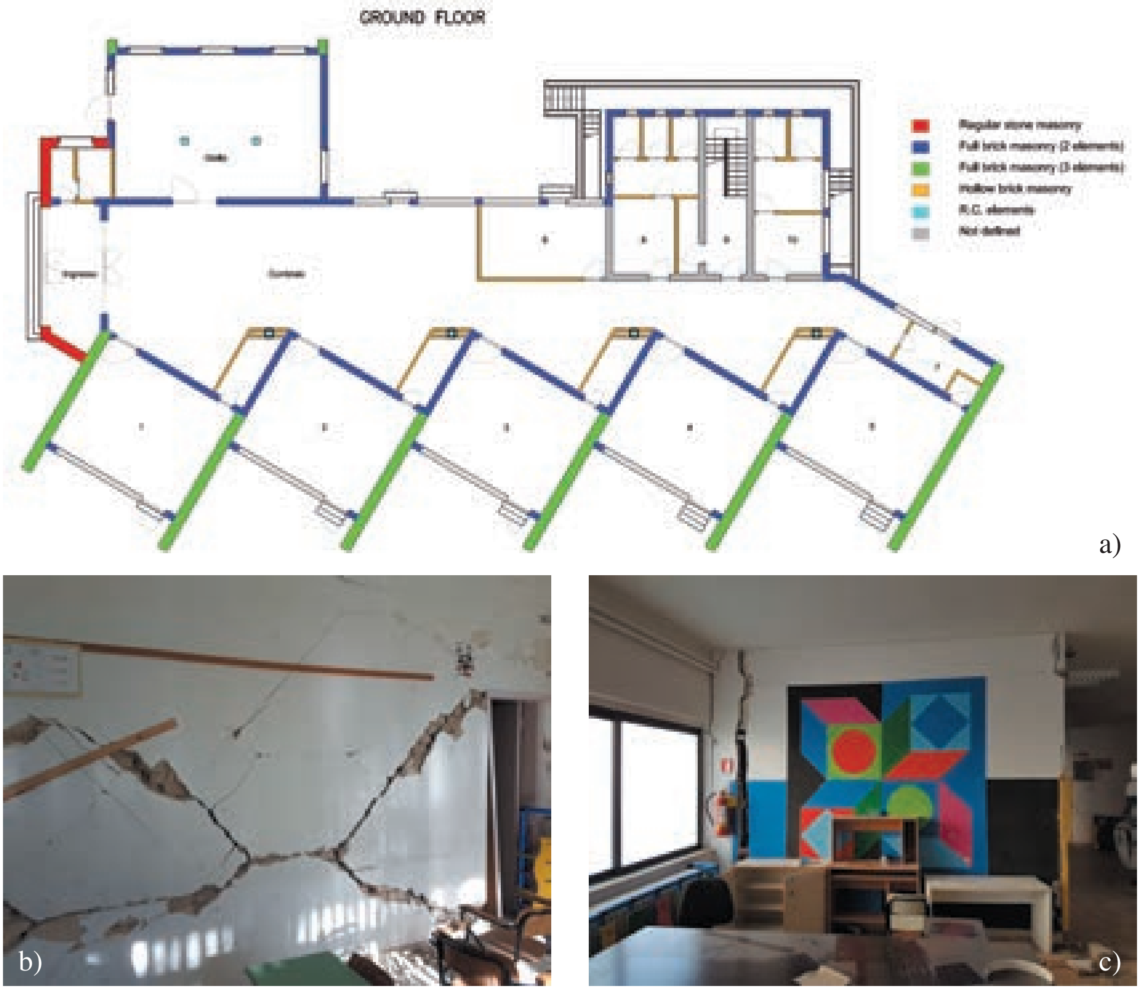


Fig. 16 - Mons. Paoletti elementary school building: a) ground floor plan with indication of structural elements; b) diagonal and c) sub-vertical cracks in non-structural masonry infills.

mixed structure, with RC frames and masonry panels with full bricks; internal infill walls are made up of hollow bricks. The foundation system consists of independent footing without any transverse connection beams; the roofing system (single-pitch roof) is a traditional RC structure with brick elements.

The school building was built in 1963, when Pieve Torina was not seismically classified, and shows the typical characteristics of the gravity load-designed RC buildings of that period, e.g., one-way frames (Fig. 16a).

The building was tagged as unusable after the earthquake that struck the region on August 24. Figs. 16b and 16c show the cracking scenario on structural and non-structural elements, with indications of horizontal, verticals and diagonal cracks. Heavy damage to both internal and external masonry partitions and out-of-plane external walls, makes the building unusable and difficult to repair.

The survey of the **B. Tucci primary school** of Acquasanta Terme (Marche) was carried out after the *M*=6.0 August 24 event.

The building is a pre-World War II two-storey masonry structure with an area of about 700 m^2 (for each floor). The complex consists of two joined buildings (Fig. 17a): the school (Building A) and the computer laboratory (Building B). The masonry of the main body (Building A, with usability rating E) was built with a vertical alternation of irregular travertine stones and clay brick sections (with spacing approximately 1 m). The RC roof is non-thrusting and the floor consists of RC hollow-core slabs. Partitions are made of solid clay brick masonry.

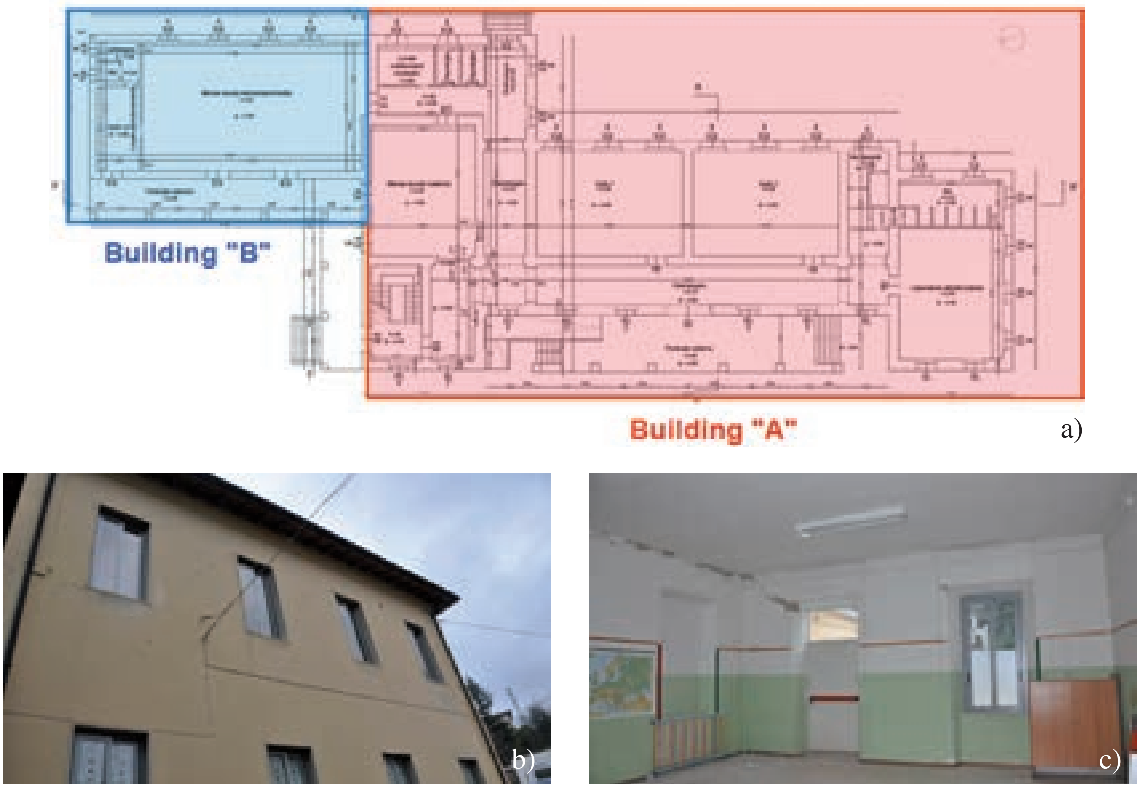


Fig. 17 - B. Tucci primary school building: a) plan view of the school complex; b) shear crack in vertical load-bearing elements; c) cracks between floor and masonry bearing walls.

The visual inspection after the M=6.0 August 24 earthquake showed significant damage to more than two-thirds of the vertical load-bearing elements (Fig. 17b) and the non-structural partition walls. Damage to spandrels was also observed. The most evident damage was due to the interaction between the masonry piers and the RC slabs (Fig. 17c), both at the first and the second floor. The stairway structure showed minor damage after the first event, which became more significant after the two October events. Falling of plaster and internal objects was observed during the inspections.

The inspection of the structure after the two October events showed a general worsening of the damage level, both in terms of crack enlargements and falling plaster. Overall, the crack pattern was found to be substantially the same as reported during the first survey. No evidence of foundation settlement was observed after the three events.

The survey of the **Don Bosco high school** of Falerone (Marche) was carried out after the M=6.0 August 24 event.

The building hosting this school is a former convent in the historic centre of Falerone, so a church form was also used to carry out the survey. This three-storey building is located on a steep slope. The original structure, built in the 14th century, has load-bearing clay masonry walls, and it is composed of two units (Fig. 18a): the church and the school/museum (total dimensions approximately 1500 m^2). External walls are made of a regular pattern of bricks, while the interior walls include different types of masonry (sometimes irregular), which were constructed in later years. In more recent years, the western portion of the building was extended by means of a RC frame. Two different roof and floor types were observed: concrete with hollow clay brick and timber. Some of the ceilings involved vaults (with and without tie rods) and dropped "camorcanna" false vaults.

Despite the long epicentral distance (almost 50 km for the first event), the first visual inspection showed damage to some masonry piers and spandrels and significant damage to non-structural partition and infill walls. The inspections revealed severe damage and partial collapse of vaulted false ceilings (Fig. 18b), detachment of plaster (Fig. 18c), and falling of internal objects. Damage to the top of the bell tower (summit cone) created a dangerous situation on the outside of the building (the cone was removed a few days after the August 24 event from the top of the bell tower).

The church in the building complex showed evidence of structural damage (e.g., detachment of the façade) and non-structural damage (e.g., shattering of the organ) (Fig. 18d).

A visit to the structure after the two large events of October (M=5.9 and M=6.5) showed a general worsening of the damage level, but the difference was not dramatic. The general crack pattern was very similar.

The **G. M. Rizzi primary school** is located in Montegallo, Balzo (Marche) at the top of a hill. The *in situ* assessment was carried out on December 9, 2016. The two-storey masonry building was built in the 1960s, and it is approximately regular in plan (Fig. 19a). The structural bearing walls are made of natural stones, poured hydraulic lime-based mortar, and two horizontal brick sections at a 1 m offset. After the seismic retrofit carried out in 2004, some new transversal walls were added, made by Poroton blocks (red walls in Fig. 19a). The floors can be considered rigid, and RC-bond beams surround them.

The site inspection showed evidence of structural damage (e.g., shear cracks on external walls) and non-structural damage (e.g., poor connection between the two types of masonry walls). Specifically, a sequence of small windows near one corner of the building strongly weakened the external wall, badly damaging a group of small squat walls during the earthquake (Fig. 19b).

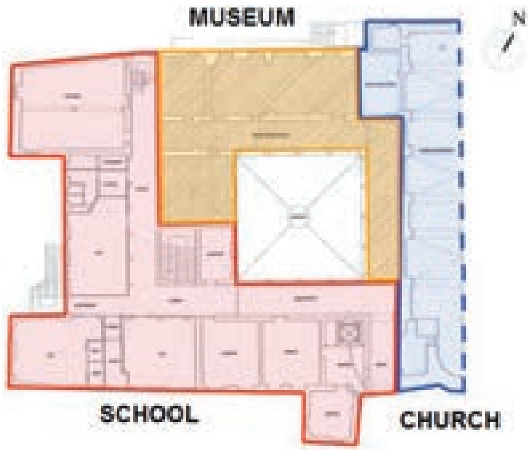
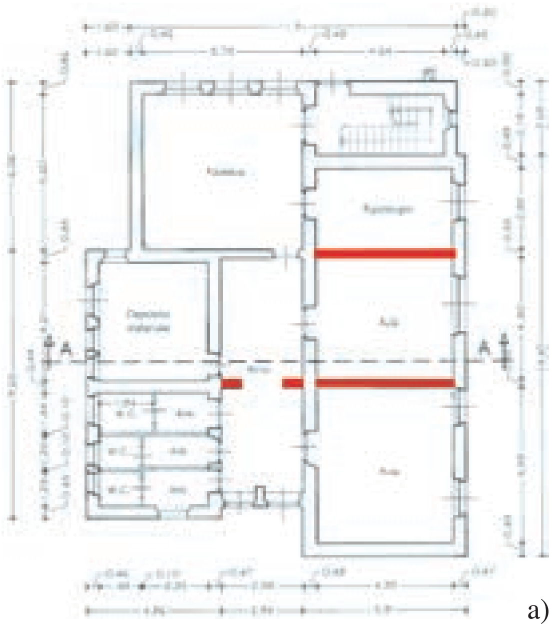


Fig. 18 - Don Bosco high school complex: a) plan view of the complex; b) false vault collapse; c) plaster expulsion with visible damage to a heater element; d) triggering of the façade overturning mechanism.

Furthermore, poor connection between internal partitions and structural bearing walls reduced the capacity of external walls to carry horizontal forces along the transverse direction.

The **elementary school of Pievebovigliana** (Marche) is a one-storey mixed structure, with masonry walls made of an inner non-structural hollow brick leaf and an outer structural leaf of poor quality (clay blocks with horizontal holes), a RC ring beam, and RC columns carrying the roof. The school was built in the 1950s, before the first Italian seismic regulation, and it was retrofitted after the 1997 central Italy earthquake: the ribbon windows were closed, and a planar frame made by welded steel beams running in orthogonal directions were built at the ceiling level to restrain possibly out-of-plane walls.



a)

b)

Fig. 19 - G.M. Rizzi primary school building: a) ground floor plan; b) strip windows and damage.

Nevertheless, the structure was still vulnerable due to planar irregularity (Fig. 20a), the narrowness of the masonry walls, especially in the lateral pavilions, and the low quality of the materials. The mortar was greatly deteriorated and could easily be pulverized by hand.

The school suffered minor damage after the August 24 earthquake, whereas it was severely damaged after the October seismic sequence. During on-site investigation carried out on December 17, strong damage was detected in the structural and non-structural elements (Fig. 20b). Severe torsional effects caused the shear failure of the inner and outer masonry walls, producing important X-shaped cracks (>1 cm), the failure of the inner non-structural brick layer, and the dislocation of the bricks of the structural masonry walls. Due to the total wearing of the bed joints from repeated sliding, some adjacent brick layers were directly in contact after the crushing and expulsion of the mortar layer.

4. Discussion and concluding remarks

The ReLUIS consortium was heavily involved in the aftermath of the 2016 central Italy earthquake. ReLUIS support to DPC consisted of technical surveys of public buildings, with emphasis on school buildings. The total number of surveys carried out by ReLUIS technicians was 253 out of 874 school structures after August 24, and 221 out of 1,015 school structures after October 26-30.

A representative set of results, for a sample size of 13 school complexes, was herein investigated in order to illustrate potential vulnerabilities of the school buildings.

From the results obtained for RC case study buildings, it can be observed that:

- RC buildings designed only for gravity loads, e.g., one-way frames, are lacking in proper lateral-resisting systems in both directions. The complete absence of an adequate structural lateral-resisting system forces the stiff infills to act as bracing systems during the earthquake.

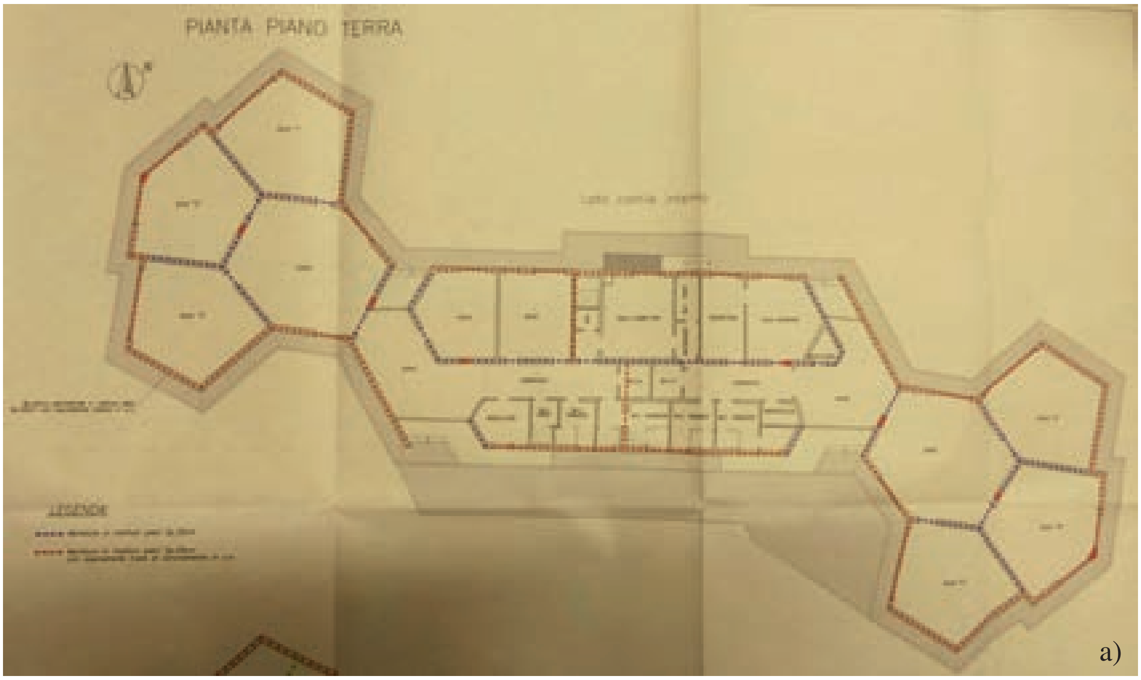


Fig. 20 - The elementary school of Pievebovigliana: a) ground floor plan; b) shear cracks in an inner wall of the east pavilion.

In this case, if infill walls are not strong enough, diffuse damage like the typical diagonal and sub-horizontal cracks are likely to be observed on internal partitions, even with minor, or moderate, intensity earthquake;

- RC buildings showed significant damage or, in several cases, the collapse of partition walls and ceilings; the observed behaviour confirms the relevance of the performance of non-structural elements in the overall response of the building, which becomes critical if the building is a school with large population exposure and a possible emergency management role;
- in case of severe earthquakes, typical damage on structural members involves beam-column joints, due to the triggering of a strut and tie mechanism of stiff infill walls, and severe damage to structural elements and buckling. Furthermore, infill collapse has also been observed, with a dangerous effect on occupants' safety;
- RC school complexes may suffer from insufficient technical joints between different buildings, especially for very irregular in-plane configuration. In this case, damage may

occur to structural joints with a seismic pounding effect between buildings, which may lead to out-of-plane behaviour of infill walls;
- seismic strengthening of partitions and infill walls as well as of beam–column joints of RC school buildings may greatly mitigate the effects of an earthquake.

From the results obtained for masonry case study buildings, it can be observed that:
- the plaster expulsion from masonry walls may lead to the unusability of schools because of non-structural damage on electrical, plumbing, and heater systems and/or other;
- masonry school complexes with a very irregular in-plane configuration suffer significantly from torsional effects, which lead to a shear failure of the inner and outer masonry walls, causing important X-shaped cracks and the dislocation of the bricks of the structural masonry walls, especially in the case of slender masonry piers and low quality materials;
- in some cases, cracks were observed at the interface between masonry piers and RC slabs. Shear cracks on external bearing walls also may occur in the case of strip windows, which lead to a strong irregular vertical configuration;
- old masonry school buildings may have damage due to insufficient transverse connection between orthogonal masonry walls, with triggering of the façade-overturning mechanism. In the case of strong motion, false vault collapse may occur;
- retrofitted masonry school buildings performed well during the earthquakes, with limited structural damage; transverse connection between masonry walls and non-structural elements may greatly mitigate the effects of the earthquake.

This finding, even if limited and related to single cases, gives preliminary but significant information on the main deficiencies of school buildings as well as on the effectiveness of strengthening interventions both for structural and non-structural elements. This can be a starting point to defining intervention strategies, priorities, and timescales aimed at significantly reducing the seismic risk of school buildings, which have a fundamental role in society.

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