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# Cumulative damage to school buildings following the 2016 central Italy earthquake sequence

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***ABSTRACT*** The 2016 central Italy earthquake highlighted the cumulative effects of a seismic sequence on the damage to buildings. In particular, the paper focuses on the behaviour of school buildings struck by several earthquakes in the seismic sequence. An initial analysis involves the correlation between the main ground motion parameters and the seismic behaviour of school buildings. The correlation between ground motion parameters and usability rating of school buildings, collected by means of the AeDES survey form, is also discussed. The analysis showed that several school buildings, usable after the first shock on 24 August 2016, resulted unusable at the end of the seismic sequence due to the extensive structural or non-structural damage. The effects of the seismic sequence are herein discussed, taking into account the school buildings' date of construction and relevant design methods, structural types (i.e. RC and masonry), and peak ground acceleration experienced in the sequence. Finally, relationships between damage and actual repair costs are used to observe the incidence of the damage provided by the seismic sequence in terms of economic losses.

**Key words:** school buildings, central Italy seismic sequence, usability and damage assessment, cumulative damage, repair intervention costs.

## 1. Introduction

Schools play a critical role in the social and cultural life of a community. The impact of school closure as a result of damage due to earthquakes is the loss of a public service resulting in social and psychological difficulties for students, faculty, and staff. The severe impact on the continuity of education and the significant social and economic losses recorded in the main earthquakes occurring in the last decades, clearly highlights the importance of improving the seismic performance of schools. Unfortunately, if an earthquake occurs when the school is fully active, then there may also be a large number of young victims. The crucial importance of schools and their vulnerability were already recognized in an OECD Ad Hoc Experts' Group Meeting on Earthquake Safety in Schools, held on 9-11 February 2004, in Paris, France. The particular architectural and structural features of schools were discussed in relation to their vulnerability (Dolce, 2004).

The $M_W$ 7.1 earthquake that recently struck central Mexico on 19 September 2017 (18:14:38 UTC) damaged more than 12,700 schools across central Mexico, with more than 2,300 schools with severe damage. The government of Mexico reported preliminary estimates that the earthquake had resulted in at least $ 2 billion in damage (from U.S. Agency for International Development, 2017).

The $M_W$ 7.8 Nepal earthquake of 25 April 2015 (06:11:26 UTC) destroyed and damaged 3,552 schools in 14 districts. Millions of children were, therefore, unable to return to schools for months unless urgent action had been taken to provide temporary learning facilities and repair the damage. The total estimated reconstruction cost of all damaged infrastructures according to the Nepal Planning Commission has been approximated at NPR 700 billion. Since schools amount to a meagre 1% of the total infrastructure damaged, the approximate reconstruction cost of schools has been estimated to be NPR 7 billion (Chen *et al.*, 2017).

The 2010-2011 Canterbury earthquake sequence in New Zealand caused severe and ongoing impacts on the social, built, economic, and natural environments in the region. A first $M_w$ 7.1 earthquake struck the Canterbury region of New Zealand at 4:35 a.m. on 4 September 2010 (3 September 16:35:45 UTC). Following the September 2010 earthquake, all schools re-opened within a couple of weeks in affected areas. After five months, on 22 February 2011 at 12:51 p.m. (21 February 23:51:43 UTC), a catastrophic $M_W$ 6.3 earthquake caused considerably greater impact with extensive damage to numerous schools. Within three weeks of the February 2011 aftershock, 84% of school students in the Christchurch area were able to attend school. However, the effects on the education system continued to go beyond the initial school closures following both the 4 September 2010 and 22 February 2011 earthquakes. More than half of secondary schools were 'site sharing', to enable two schools to use one school facility every day. Over 12,000 school students left their school and enrolled elsewhere, including at schools outside the region (Mutch, 2014).

The $M_W$ 7.2 El Mayor Cucapah (Baja California) earthquake of 4 April 2010 (22:40:42 UTC) caused significant structural damage to several schools in Mexico and significant non-structural damage to several schools in the U.S. The state government decided to delay the return to school for 13,000 students in the 57 schools affected by the earthquake because the climate was too hot for education in tents or mobile classrooms without air conditioning. Non-structural issues were significant especially in some school buildings in Calexico and at a university campus in Mexicali. Collapse of non-structural features could have resulted in potential fatalities, had the school or university been in session during the earthquake. As of 30 April 2010, several schools were still closed and under repair (Rodgers, 2012).

On 12 May 2008 an $M_W$ 7.9 earthquake struck south-western China, centred in Wenchuan county. More than 7,444 schools were damaged and at least 15,000 children lost their lives in schools (Yang *et al.*, 2011). As of May 2011, China had spent $123 billion to rebuild areas affected by the 2008 earthquake. Nearly 3,000 schools and more than 1,200 health care facilities had been rebuilt or repaired, along with millions of houses (source by Chinese government).

The strong earthquakes which occurred in Italy in the last decades, Molise (2002), Abruzzo (2009), Emilia (2012) and, very recently, central Italy (2016-2017), confirmed the vulnerability of existing structures and school buildings (Di Ludovico *et al.*, 2012, 2017a, 2017b, 2017c; Frascadore *et al.*, 2015; Del Gaudio *et al.*, 2016; Dolce *et al.*, 2016).

The collapse of the Iovene primary school in San Giuliano during the 2002 Molise earthquake caused the death of 27 children and a teacher; following this event a new seismic code was issued in Italy by an ordinance of the Prime Minister (O.P.C.M. 3274, 2003). The ordinance introduced an update of the Italian territory seismic hazard, through the definition of four seismic zones as well as the mandatory seismic capacity assessment of all public strategic and critical buildings, including schools, in medium and high hazard areas in order to set up a seismic rehabilitation.

In the aftermath of the $M_W$ 6.3 L'Aquila earthquake of 6 April 2009 (01:32:39 UTC), usability assessment was carried out on 62 schools (for a total of 156 structures) in L'Aquila city, and 234 schools (for a total of 324 structures) in L'Aquila province (64 different municipalities). The synergy between the Civil Protection Department (DPC), the Network of Seismic University Laboratories (ReLUIS), the Public Works Office, and the municipalities and province of L'Aquila allowed school buildings assessed as A (usable) to be re-opened before summer and to regularly perform the exams at the end of the academic year. Further, repair/strengthening work was undertaken on 41 schools (hosting about 8,300 students) assessed as B (usable only after short-term countermeasures), with a total cost of € 27 million; the whole stock of school buildings assessed as B re-opened by 5 October 2009 (Del Vecchio *et al.*, 2015; Frascadore *et al.*, 2015).

The 2012 seismic sequence that struck the Emilia region was characterized by seven events with an $M_W$ 5.0 and larger. Most of observed damage involved masonry buildings, prefabricated industrial structures, and, in some cases, reinforced concrete (RC) buildings. However, the earthquake sequence also resulted in 200 school buildings with structural or non-structural damage (Dolce *et al.*, 2016).

Following the 2016 central Italy earthquake sequence, the damage and usability assessment was carried out on 1,514 buildings (i.e. buildings and sports facilities of pre-primary, primary, high schools, and universities). At the end of the sequence, 531 school buildings (35% of the database) resulted partially or totally unusable due to structural or non-structural damage. A detailed discussion on the most frequent observed damage types on structural and/or non-structural elements of masonry and RC school buildings is reported in Di Ludovico *et al.* (2017c). Observations on damage and response of school buildings inspected all over the four regions is reported in Di Ludovico *et al.* (2018).

The 2016 central Italy earthquake highlighted the effects of a seismic sequence in terms of cumulative and progressive damage observed on school buildings, re-inspected after each new seismic event. In particular, school buildings that were assessed as usable after the first shock on 24 August, 2016, resulted unusable at the end of the sequence, partially or totally, due to extensive structural or non-structural damage.

A preliminary evaluation of cumulative damage on RC buildings that were struck and damaged by the 2012 Emilia earthquake sequence (20 and 29 of May) is reported in Verderame *et al.* (2014). In particular, the cumulative damage effect was obtained, based on the evaluation of the residual capacity of damaged structures, to be compared with observed damage. The results of that procedure showed that a certain percentage of buildings shifted from light damage to higher damage due to the reduced (residual) seismic capacity of a damaged structure and because of the higher values of peak ground acceleration (*PGA*) recorded during the event of 29 May in some municipalities.

This paper analyses the effects of the seismic sequence in terms of damage detected on school buildings surveyed during the 2016 central Italy earthquake. Firstly, the influence of the main ground motion parameters on seismic behaviour of buildings usability is investigated. Then, the structural characteristics of the buildings are analysed, based on the inventory of the data collected using the AeDES ‟Building Operability and Damage during the Post-Earthquake Emergency" survey form for usability and damage of buildings (Baggio *et al.*, 2007), whose most recent official version can be found in (DPCM 14.01.2015). The analyses involve school buildings grouped in classes according to structural type and design methodology, as well as to the recorded excitation expressed in terms of *PGA*. Finally, the incidence of the damage induced by the seismic sequence in terms of economic losses related to direct repair intervention costs is investigated. For this purpose, the relationship between the usability rating of school buildings and the actual repair costs per square metre, calibrated on the reconstruction projects related to residential buildings damaged by 2009 L'Aquila earthquake, has been taken into account (De Martino *et al.*, 2017).

## 2. The central Italy earthquake sequence

On 24 August 2016 (01:36:32 UTC) an $M_W$ 6.0 earthquake hit four regions of central Italy (i.e. Abruzzo, Lazio, Marche, Umbria); the quake epicentre was close to Amatrice, Accumoli, and Arquata del Tronto and caused widespread building collapses and about 300 casualties.

Two months after, on 26 October 2016, two aftershocks, $M_W$ 5.4 (17:10:36 UTC) and $M_W$ 5.9 (19:18:06 UTC) extended the seismogenic volume to the NW. After 4 days, on 30 October 2016 (06:40:18 UTC), an $M_W$ 6.5 earthquake struck the area of the Sibillini Mountains with epicentre close to Norcia, Umbria region. The latter earthquakes caused extensive damage especially to many historical buildings, but no fatalities and few injuries were recorded.

On 18 January 2017 a short sequence of four earthquakes with $M_W$ larger than 5 struck 25 km NW of L'Aquila, starting at 09:25:40 UTC with $M_w$ 5.1 and ending at 13:33:36 UTC, with the fourth tremor of magnitude $M_w$ 5.0. The two strongest events occurred at 10:14:09 UTC, with $M_W$ 5.5. and 11 minutes later with $M_W$ 5.4.

The central Italy earthquake sequence resulted in thousands of buildings with structural or non-structural damage. The damage and seismic usability assessment of public and private buildings started immediately after the earthquake in order to evaluate the safety conditions and enable people to return to their social and business activities. The AeDES survey form was used as a first level survey and filled on the basis of visual in-situ inspection of the building. It allowed buildings to be classified into the following main categories: A = usable buildings; B or C (B-C in the following) = building usable only after short-term countermeasures or partially usable; E = unusable building. Note that the usability form refers to the minimum structural unit of ordinary buildings, i.e. one building. Priority was given to public buildings, primarily schools. After the entire seismic sequence, the AeDES form was compiled for 1,514 school buildings. The database includes 678 RC buildings, 502 masonry buildings, 188 buildings with a mixed structural type (i.e. comprising RC and masonry structural members), steel structure or other types and 146 sport facility buildings. Figs. 1a to 1d summarize the data collected in each usability rating class for different structural types and show that RC is the most common structural type in buildings with

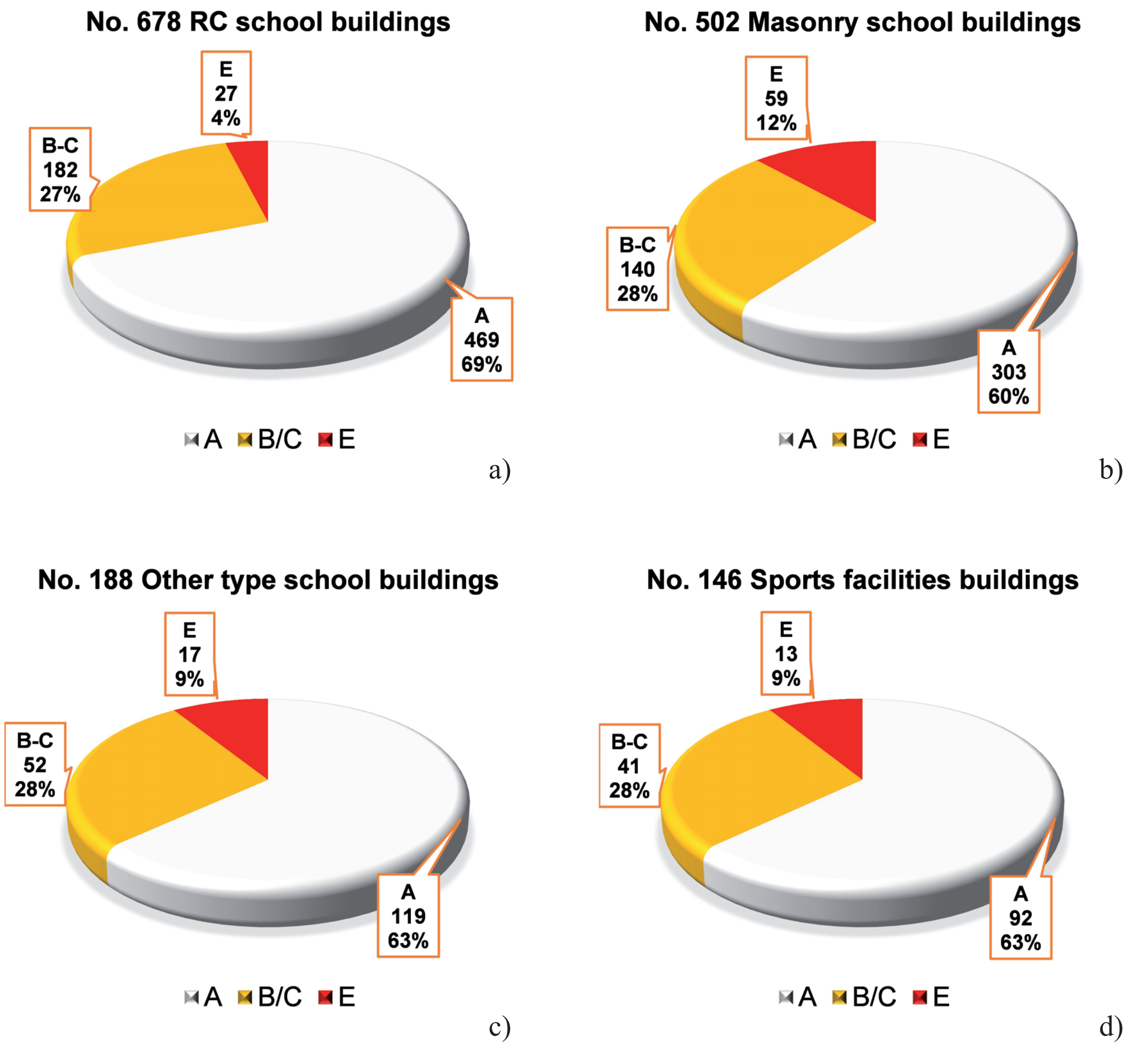


Fig. 1 - Percentage of inspected school buildings classified as usable or unusable after the entire seismic sequence: RC buildings (a); masonry buildings (b); other type buildings (c); sport facility buildings (d).

usability rating A: 69% usable and 31% unusable (i.e. 27% B-C and 4% E rating, respectively); by contrast, masonry is the most common structural type in the case of buildings with usability rating E: 60% usable and 40% unusable (i.e. 28% B-C and 12% E rating, respectively).

## 3. Usability rating vs. earthquake intensity

Figs. 2a to 2d show the distribution of usability ratings for the total of 1,514 school buildings inspected after the entire seismic sequence, as a function of the maximum values of ground motion parameters recorded during the seismic sequence, namely the *PGA* (Fig. 2a), the peak ground velocity (*PGV*, Fig. 2b), the spectral acceleration at 0.3 s period 5% damping (*PSA0.3*, Fig. 2c), and the spectral acceleration at 1.0 s period 5% damping (*PSA1.0*, Fig. 2d). For each

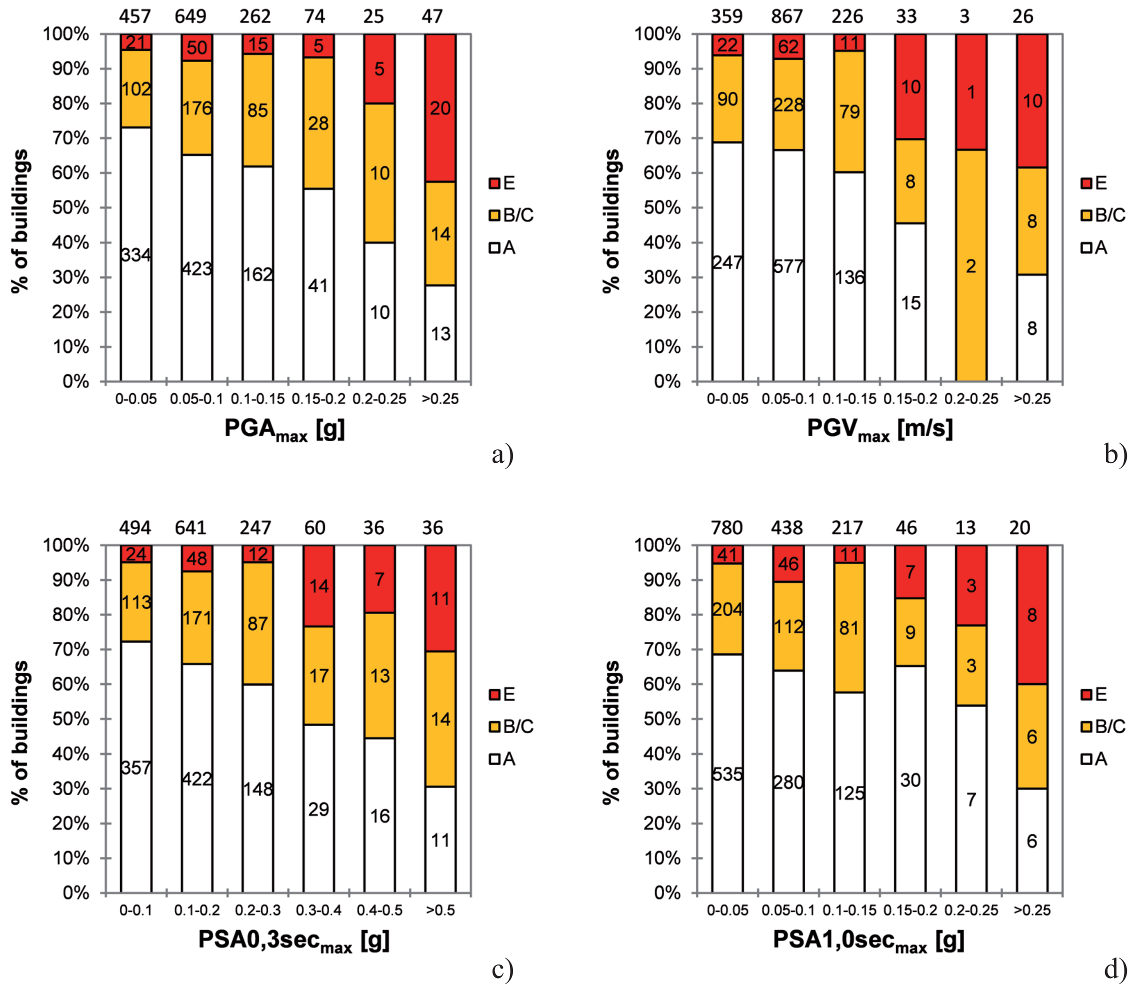


Fig. 2 - Distribution of usability ratings of the school buildings as a function of the maximum values of the ground motion parameters recorded during the seismic sequence: *PGA* (a), *PGV* (b), *PSA0.3* (c), *PSA1.0* (d).

school building, the corresponding maximum ground motion parameter value is extrapolated from the shake maps provided by the Istituto Nazionale di Geofisica e Vulcanologia (INGV, http://shakemap.rm.ingv.it/shake/index.html). More details on how local soil conditions are taken into account in evaluating *PGA* can be found in Michelini *et al.* (2008).

The usability rating distribution trend as a function of ground motion parameters shows a similar trend with respect to *PGA*, *PGV*, *PSA0.3*, and *PSA1.0*. In particular, the percentage of usable school buildings inspected after the entire seismic sequence ranges from nearly 70 to 30% with increasing intensity level.

In order to establish the influence of the ground motion parameters on usability rating, the effect of each single parameter is investigated, for the $M_W$ 6.0 24 August 2016 event, considering its standardized value $x_j$:

$$x_j = \frac{X_j - \left(X_{j,\max} + X_{j,\min}\right)/2}{\left(X_{j,\max} - X_{j,\min}\right)/2} \quad (1)$$

where $X_{j,max}$ and $X_{j,min}$ are the higher and lower values, respectively, of the $j^{th}$ variable (i.e. *PGA*, *PGV*, *PSA0.3*, and *PSA1.0*), recorded in the $M_W$ 6.0 24 August 2016 event, see Table 1.

Note that the analysis refers only to the 24 August seismic event because data (i.e. usability rating) is less affected by uncertainties related to the effect of the seismic sequence.

Table 1 - Minimum and maximum values of ground motion parameters, $M_W$ 6.0 24 August 2016.

| | $M_w$ 6.0 August 24, 2016 | |
|---|---|---|
| Variable | $X_{j,min}$ | $X_{j,max}$ |
| $x_1 = PGA$ [g] | 0.010 | 0.756 |
| $x_2 = PGV$ [m/s] | 0.015 | 0.422 |
| $x_3 = PSA0.3$ [g] | 0.027 | 1.538 |
| $x_4 = PSA1.0$ [g] | 0.011 | 0.257 |

Figs. 3 and Table 2 show the correlation between each single codified variable and the usability rating (indicated as = 1 if the building was unusable and = 0 if usable). In Fig. 3 the dot lines represent the simple linear interpolation line that describes the relative weight of model parameter $X_j$ (codified as $x_j$) on response $Y$, i.e. on usability rating. In Table 2 the regression line is evaluated for each single variable.

With reference to the $M_W$ 6.0 24 August 2016 event, *PGA* and *PSA0.3* proved the most influential parameters to correlate damage and relevant usability rating and seismic excitation. (Fig. 3). However, as expected, the variables $x_1$ (*PGA*), $x_2$ (*PGV*), and $x_3$ (*PSA0.3*) are highly mutually correlated.

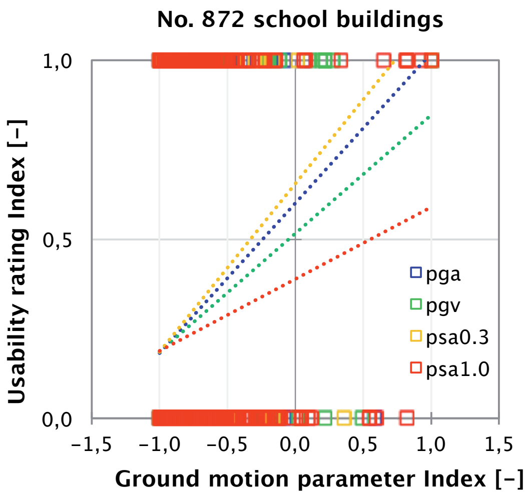


Fig. 3 - Influence of single variables on usability rating (0 = usable, 1 = unusable).

Table 2 - Correlation of single variables on damage.

| Variable | Equation |
|---|---|
| $x_1 = PGA$ [g] | $y = 0.4186x + 0.6007$ |
| $x_2 = PGV$ [m/s] | $y = 0.3305x + 0.5161$ |
| $x_3 = PSA0.3$ [g] | $y = 0.4698x + 0.6553$ |
| $x_4 = PSA1.0$ [g] | $y = 0.2006x + 0.3888$ |

In order to analyse the effects of the seismic sequence on damage, several authors have emphasized that elastic spectral values provide a better correlation with empirical damage data than *PGA* (Spence *et al.*, 1992; Singhal and Kiremidjian, 1996; Rossetto, 2004). In any case, the main critique associated with using elastic spectral values is the determination of equivalent vibration periods. Typically, the empirical relationships reported in seismic building codes (CEN, 2004) to characterize the elastic period of vibration tend to provide conservatively low values of the structural effective period, resulting in higher spectral acceleration values and consequently in higher design forces. For this reason, in the following the effects of the seismic sequence on damage detected on school buildings will be analysed in terms of *PGA*.

## 5. School buildings data set

The area struck by the central Italy earthquake sequence was very large and because seismic codes and seismic hazard classifications have evolved over time, several school buildings in the data set were built before the development of modern seismic design provisions or for gravity load only (i.e. not considering seismic provisions at all).

The evolution of the seismic classification for each municipality of the data set has been determined by means the ECS-it software provided by ReLUIS (http://www.reluis.it). The ECS-it software is a Geographic Information System (GIS) that allows the visualization and the return at national scale on the evolution of the seismic classification of the national territory in a period of time from 1909 to 2003. The software allows running a search for each municipality or for the entire national territory the evolution of the seismic classification according to the issuing of laws and decrees over the years.

The number of buildings related to different construction age periods and number of storeys, as well as their cumulative percentages, are presented in Figs. 4a to 4d for RC and masonry buildings, respectively. The construction age is grouped according to thirteen periods as adopted in the latest AeDES form version. Note that the construction age period is unknown for 17 out of 678 RC school buildings and 10 out of 502 masonry school buildings, respectively.

Fig. 4a shows that 87% of the RC building data set (corresponding to 590 buildings) have less than 4 storeys. The number of RC buildings starts to be significant in periods after 1961 (see Fig. 4b), with peaks of 158 buildings in 1962-1971 (corresponding to 24% of the RC building data set). By contrast, Figs. 4c and 4d show that the number of masonry buildings is almost the same for periods before 1971, while it decreases notably for periods after 1971. Most of the masonry buildings have between 1 and 3 storeys (434 buildings corresponding to 86% of the masonry building data set).

Figs. 4a to 4d refer to two seismic design classes of buildings: ‘‘S’’ stands for seismic design (buildings built in a municipality that was already classified as ‘‘seismic’’ at the time of construction) and ‘‘NS’’ for no-seismic design (buildings built in a municipality before anti-seismic structural solutions were adopted in the design of buildings). Note that most buildings are in the class “S” but they were designed to sustain horizontal actions according to obsolete seismic provisions.

Table 3 summarizes the usability rating of buildings in each structural type and seismic design class. The table shows that masonry buildings designed with older and/or outdated standards (i.e. no-seismic design, NS) was the most common structural type in the case of buildings with damage to non-structural parts (i.e. 34% B-C usability rating) and with severe damage to structural parts (i.e. 13% E usability rating). By contrast, the behaviour of masonry buildings designed to sustain horizontal actions (i.e. seismic design, S) was definitely satisfactory for 80% of the relevant data set. As concerns RC school buildings, slight differences resulted between buildings designed for gravity load only (i.e. not considering seismic provisions at all, NS) and buildings designed to sustain seismic load (i.e. seismic design, S): 29 and 33% of unusability for S and NS, respectively.

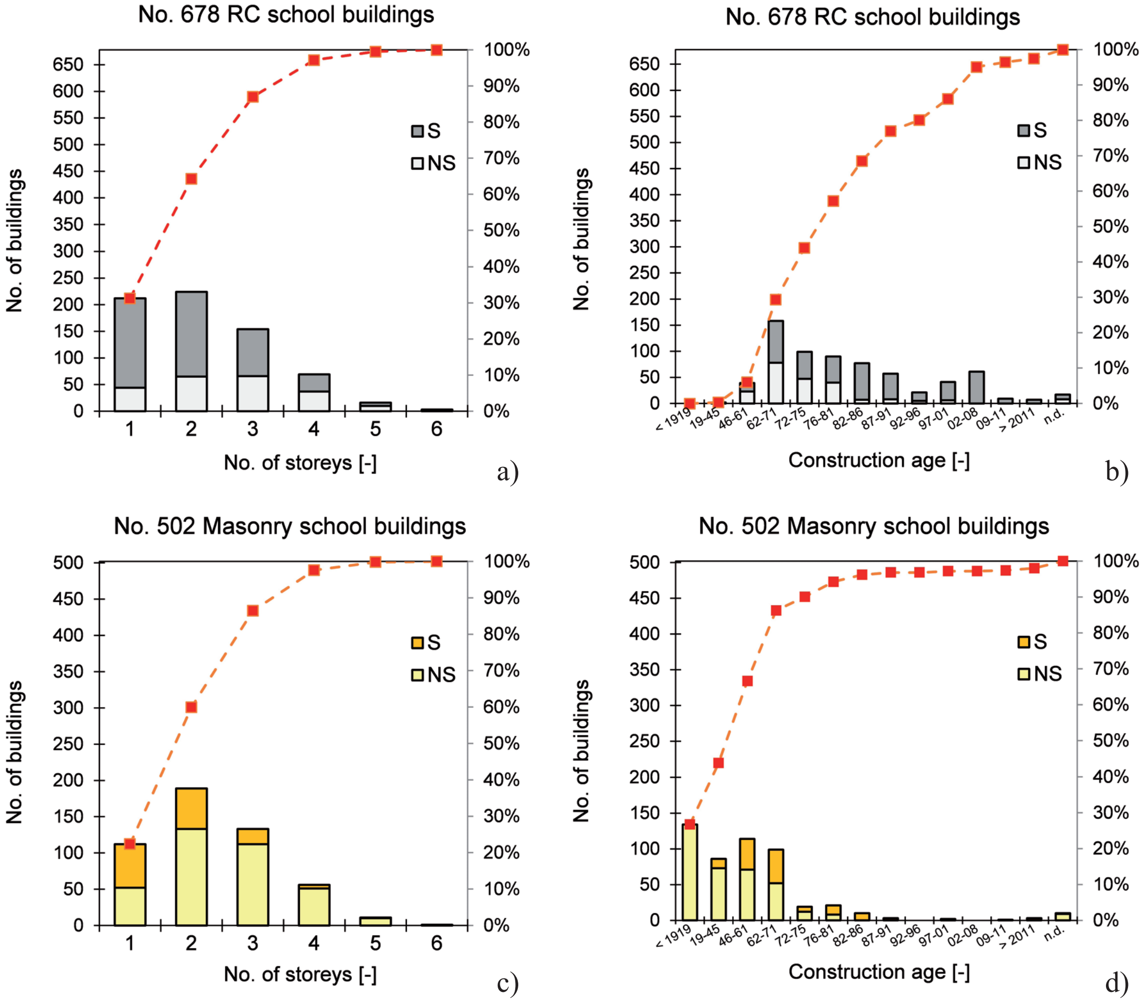


Fig. 4 - Number of storeys and construction age of inspected school buildings: RC buildings (a, b); masonry buildings (c, d).

Table 3 - Number of school and sport facility buildings in each usability rating class and structural type.

| Building stock | Structural type | Usability rating | No. of buildings | | % of buildings | No. of buildings | | % of buildings |
|---|---|---|---|---|---|---|---|---|
| | | | NO-SEISMIC DESIGN (*NS*) | | | SEISMIC DESIGN (*S*) | | |
| **1,514** | RC schools | A | 224 | 149 | 67% | 474 | 320 | 71% |
| | | B-C | | 63 | 28% | | 119 | 26% |
| | | E | | 12 | 5% | | 15 | 3% |
| | Masonry schools | A | 359 | 189 | 53% | 143 | 114 | 80% |
| | | B-C | | 122 | 34% | | 18 | 12% |
| | | E | | 48 | 13% | | 11 | 8% |
| | Other type schools | A | 131 | 82 | 63% | 57 | 37 | 65% |
| | | B-C | | 33 | 25% | | 19 | 33% |
| | | E | | 16 | 12% | | 1 | 2% |
| | Sports facilities | A | 75 | 46 | 61% | 71 | 46 | 65% |
| | | B-C | | 21 | 28% | | 20 | 28% |
| | | E | | 8 | 11% | | 5 | 7% |

## 6. Effects of the seismic sequence

This section focuses on the effects of the seismic sequence in terms of damage observed on school buildings after each main shock. The damage is again characterized in terms of usability rating. Out of a total of 1,514 school buildings inspected after the entire seismic sequence, the analysis refers to 363 buildings (226 RC and 137 masonry structural types) inspected more than once in the seismic sequence. In particular, the data set consists of school buildings classified with A and B-C usability rating after the 24 August 2016 event, and re-inspected after the 30 October 2016 event. Note that school buildings classified with E usability rating after the 24 August seismic event were no longer inspected after October events since already unusable for a long period after the first event, and, therefore, are not included in the considered sample.

Figs. 5 and 6 show the usability rating of the school buildings of the data set as a function of the recorded *PGA* of the two main events, 24 August, $PGA_{\mathrm{Aug24}}$, and 30 October, $PGA_{\mathrm{Oct30}}$. The points belonging to the black dash-dot line represent *PGA* during 24 August equal to that of 30 October. Thus, the points in the areas between black and blue (or black and red) dash-dot line represent school buildings located in areas where the recorded October seismic intensity was higher than the August one by a factor between 1-2 (or 1-3). It is worth noting that over 95% of school buildings of the sample are located in areas with *PGA* lower than 0.15 g. Figs. 5a and 6a collect the points related to school buildings for which the usability rating was confirmed after the October seismic event (A and B-C usability rating), while Figs. 5b and 6b indicate buildings that changed from A to B-C, A to E, or B-C to E usability ratings, respectively.

From the data collected by filling the AeDES forms, 263 out of 363 school buildings (168 RC and 95 masonry structural types), corresponding to 72% of the data set, showed no change in their usability rating, even in case of significant increase (up to 3 times) of the recorded seismic intensity level. The remaining 28% of the data set (58 RC and 42 masonry school buildings), rating A or B-C during the first survey, resulted partially or totally unusable after the October shocks. In some cases, this also happened for buildings that experienced a lower *PGA* in October than that recorded in August, as shown in Figs. 5b and 6b. In particular, 48 RC school buildings, usable after the 24 August shock, became unusable after the October event (45 rating B-C and 3 rating E, respectively), while 10 RC school buildings, unusable but usable only after short-term countermeasures (rating B-C), changed to an E rating after the October earthquake. Moreover, 34 masonry buildings, usable after the 24 August shock, became unusable after October event (24 rating B-C and 10 rating E, respectively), while 8 masonry school buildings, unusable but usable only after short-term countermeasures (rating B-C), changed to an E rating after the October seismic event.

The number and the percentage of school buildings with changing or not usable rating after the October event are summarized in Table 4 according to structural type (RC and masonry). The collected data have been grouped in two categories according to the recorded *PGA* of the two seismic events: i) buildings with recorded $PGA_{\mathrm{Oct30}}$ higher than $PGA_{\mathrm{Aug24}}$; ii) buildings with recorded $PGA_{\mathrm{Oct30}}$ equal or lower than $PGA_{\mathrm{Aug24}}$.

Table 4 shows that 189 out of 226 RC school buildings, corresponding to 84% of RC data set, experienced $PGA_{\mathrm{Oct30}}$ higher than $PGA_{\mathrm{Aug24}}$, while the remaining 16% of data set (i.e. 37 buildings)

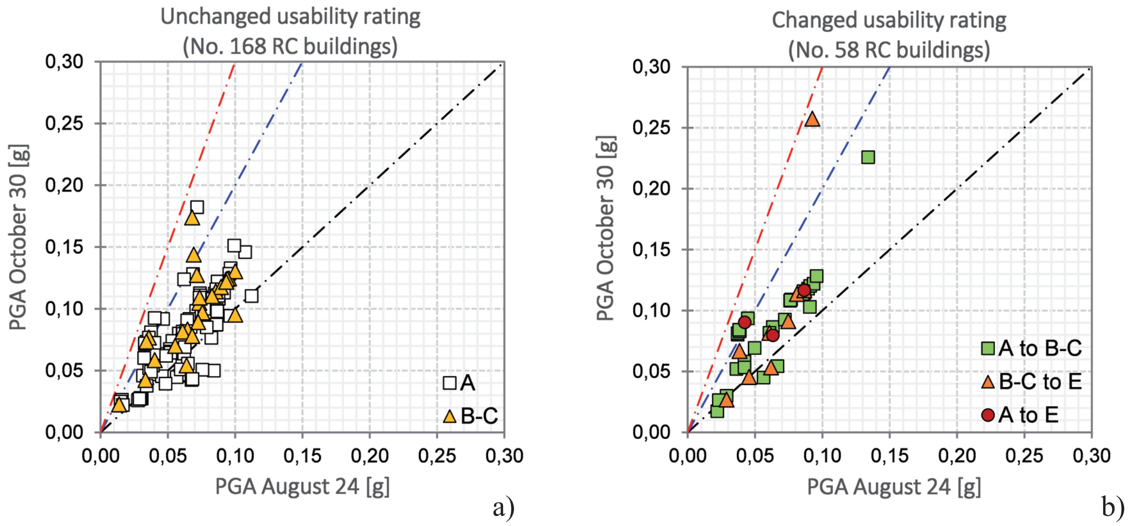


Fig. 5 - *PGA* of RC school buildings inspected both after the 24 August and the 30 October 2016 seismic events: buildings unchanging usability rating (a); buildings changing usability rating (b).

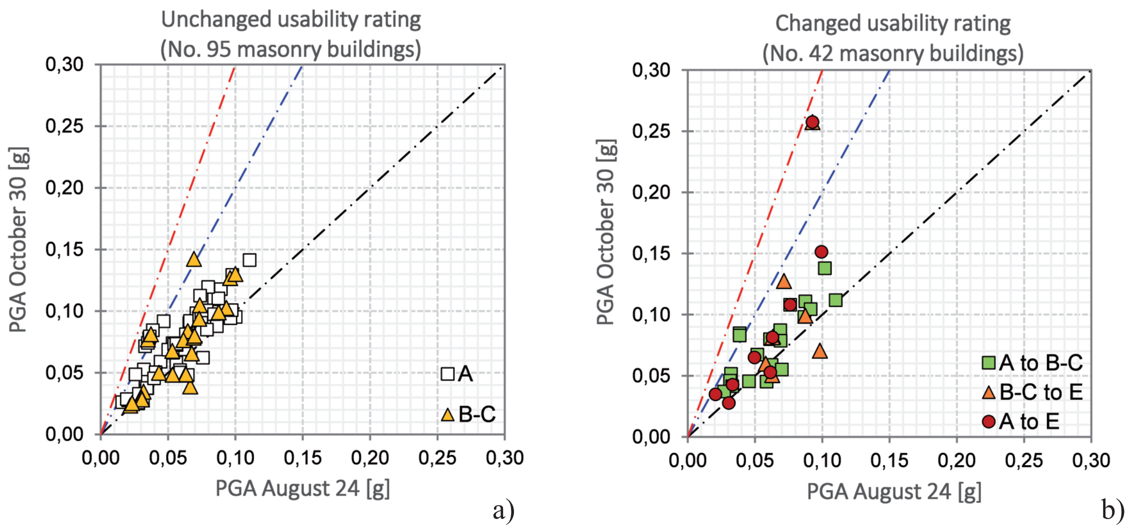


Fig. 6 - *PGA* of masonry school buildings inspected both after the 24 August and the 30 October 2016 seismic events: buildings unchanging usability rating (a); buildings changing usability rating (b).

concerns school buildings located in municipalities that experienced $PGA_{Oct30}$ lower or equal to $PGA_{Aug24}$. The table shows that for $PGA_{Oct30}$ higher than $PGA_{Aug24}$ the usability rating has been confirmed for a significant percentage of RC school buildings (i.e. 73%) while 27% of the data set changed usability rating. The remaining 37 out of 226 RC school buildings, which experienced $PGA_{Oct30} \leq PGA_{Aug24}$, mostly unchanged their usability rating (i.e. 81%) and only 19% became unusable due to an increased damage level of structural or non-structural components.

Regarding masonry school buildings, Table 4 shows that 69% of the data set of buildings, which experienced $PGA_{Oct30}$ higher than $PGA_{Aug24}$ (i.e. 74 out of 108 school buildings), has confirmed the

Table 4 - Number and percentage of RC and masonry school buildings in each usability rating and structural type grouped according to the recorded *PGA*.

| Building stock | Structural type | Usability rating | $PGA_{Oct30} > PGA_{Aug24}$ | | | $PGA_{Oct30} \leq PGA_{Aug24}$ | | |
|---|---|---|---|---|---|---|---|---|
| | | | No. of buildings | | % of buildings | No. of buildings | | % of buildings |
| **363** | 226 RC school buildings | A | **189** | 102 | 54% | **37** | 28 | 76% |
| | | B-C | | 36 | 19% | | 2 | 5% |
| | | A to B-C | | 42 | 22% | | 3 | 8% |
| | | B-C to E | | 6 | 3% | | 4 | 11% |
| | | A to E | | 3 | 2% | | 0 | 0% |
| | 137 masonry school buildings | A | **108** | 55 | 51% | **29** | 13 | 45% |
| | | B-C | | 19 | 18% | | 8 | 28% |
| | | A to B-C | | 20 | 19% | | 4 | 14% |
| | | B-C to E | | 6 | 6% | | 2 | 7% |
| | | A to E | | 8 | 7% | | 2 | 7% |

usability rating. By contrast, in the range of $PGA_{Oct30} \leq PGA_{Aug24}$, 8 out of 29 buildings became unusable (i.e. B-C or E usability rating) after the October earthquake.

Furthermore, the data collected in Table 4 shows that the effects of a new seismic event with a lower *PGA* than the previous one resulted in a change of the usability rating for about one out of five or four for RC and masonry buildings, respectively. In case of a new event with a higher intensity than the previous one, almost one RC building out of three or four and one masonry building of three became unusable due to an increased damage level of structural or non-structural components.

Note that the damage could also have been characterized on the basis of the results reported at section 4 of the AeDES survey form, which accounts for the level and extent of the damage to each structural component. By using such data, it is possible to derive a direct damage level increase in buildings which changed usability rating. In particular, for those buildings, Table 5 summarizes the damage level related to vertical structures, $D_{VS}$, computed according to the following equation (Dolce *et al.*, 2001):

$$D_{VS} = \frac{\sum_{D=D_0}^{D_5} D \cdot e_{k,D}}{5} \tag{2}$$

where $D$ is the damage level ($D_0$ = 0; $D_1$ = 1; $D_2$–$D_3$ = 2.5; $D_4$–$D_5$ = 4.5), and $e_{k,D}$ is the damage level extent, ranging between 0 and 1, which has to vary depending on the damage extent, $k$: less than 1/3, between 1/3 and 2/3, and greater than 2/3. The range of values of $e_{k,D}$, and $D \cdot e_{k,D}$ for both RC and masonry structural types are reported in Dolce *et al.* (2001).

The table shows that the damage level significantly increased in case of school building that change usability rating especially for buildings that became unusable due to severe damage to structural members (i.e. E usability rating).

Table 5 - Damage to vertical structures of RC and masonry school buildings inspected both after the 24 August and the 30 October seismic events in each usability rating and structural type.

| Structural type | Usability rating | $PGA_{Oct30} > PGA_{Aug24}$ | | | $PGA_{Oct30} \leq PGA_{Aug24}$ | | |
|---|---|---|---|---|---|---|---|
| | | Average $D_{VS}$ [-] | | Average $\Delta D_{VS}$ [-] | Average $D_{VS}$ [-] | | Average $\Delta D_{VS}$ [-] |
| | | 24 August | 30 October | | 24 August | 30 October | |
| 226 RC school buildings | A | 0.00 | 0.00 | **0** | 0.00 | 0.00 | **0** |
| | B-C | 0.11 | 0.11 | **0** | 0.21 | 0.21 | **0** |
| | A to B-C | 0.01 | 0.07 | **+0.06** | 0.17 | 0.17 | **0** |
| | B-C to E | 0.17 | 0.30 | **+0.13** | 0.13 | 1.34 | **+1.21** |
| | A to E | 0.00 | 0.43 | **+0.43** | - | - | - |
| 137 Masonry school buildings | A | 0.00 | 0.00 | **0** | 0.00 | 0.00 | **0** |
| | B-C | 0.26 | 0.28 | **+0.02** | 0.30 | 0.30 | **0** |
| | A to B-C | 0.14 | 0.30 | **+0.16** | 0.19 | 0.43 | **+0.24** |
| | B-C to E | 0.28 | 1.05 | **+0.77** | 0.60 | 1.25 | **+0.65** |
| | A to E | 0.09 | 1.20 | **+1.11** | 0.21 | 0.46 | **+0.25** |

## 7. Damage vs. actual repair costs

This section investigates the relationship between the usability rating of re-inspected school buildings (i.e. 363 buildings, 226 RC and 137 masonry structural types) and the actual repair costs per square metre. The goal is to observe the incidence of the damage provided by the seismic sequence in terms of economic losses related to direct repair intervention costs. To this end, a suitable damage factor, *DF*, has been assessed according to De Martino *et al.* (2017) for each school building inspected after the two main seismic events. *DF* takes into account not only the damage level and extent on each building component but also the weight of the damage on a single component on the total repair costs of the building. Note that it was calibrated on the data related to the reconstruction projects of residential building damaged by the 2009 L'Aquila earthquake; thus, for school buildings, the burden of buildings component damage on repair costs may be slightly different. However, no data are currently available to refine the calibration of *DF*.

Figs. 7a and 7b compare the percentage distributions of the assessed *DF* for RC (Fig. 7a) and masonry (Fig. 7b) school buildings for both the 24 August and the 30 October, 2016 events. Note that a significant part of the data set resulted undamaged after both seismic events (i.e. $DF = 0$), see Table 4. Fig. 7a shows that after the 30 October event the percentage of buildings belonging to *DF* from 0.05 to 0.20 increased by 4-7%; the trend of *DF* frequency clearly shows that the second seismic event led to an average increase of the global damage on RC structures. In case of masonry buildings, Fig. 7b shows a decreasing percentage of buildings with *DF* lower than 0.05 after the two seismic events (i.e. 72 vs. 58%); the occurrence of a new major seismic event resulted in higher *DF* for the subset in the range of *DF* from 0.05 to 0.25 (i.e. *DF* increased by a factor ranging between 2-9%).

Once *DF* has been computed, the related actual repair costs per square metre have been assessed for each building according to the functions reported in De Martino *et al.* (2017), Eqs. 3 and 4. In particular, the costs have been expressed as *Cr* (Building Repair Cost Ratio) that expresses a dimensional cost ratio obtained as a ratio between the actual repair costs related to the

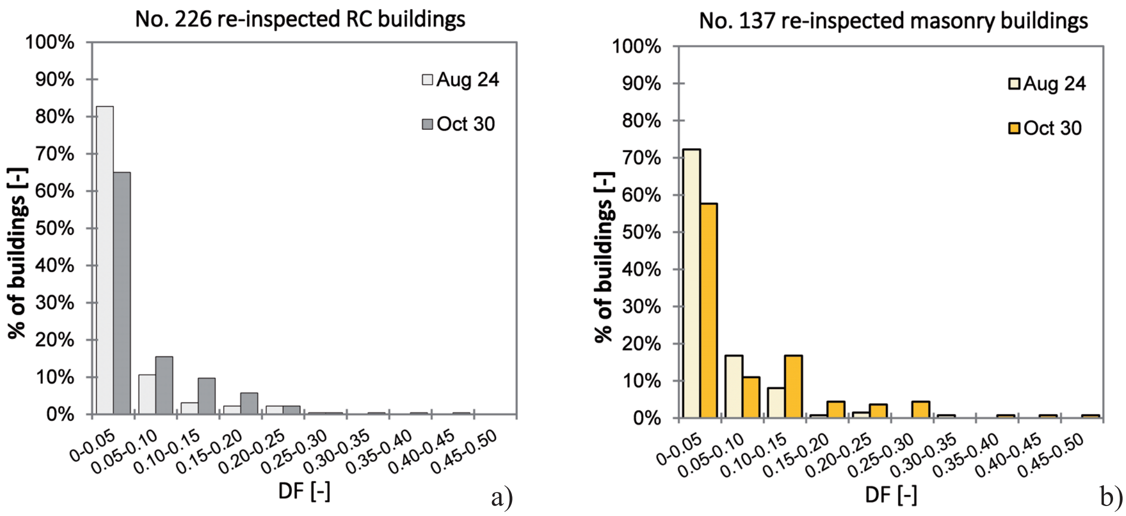


Fig. 7 - Percentage distributions of *DF* assessed for school buildings inspected both after the 24 August and the 30 October seismic events: RC buildings (a); masonry buildings (b).

building and the average reconstruction cost of private residential buildings damaged by L'Aquila earthquake (De Martino *et al.*, 2017).

*RC buildings:* $Cr = 0.09 + 1.1DF - 0.4DF^2$ (3)

*Masonry buildings:* $Cr = 0.12 + 0.71DF - 0.23DF^2$ (4)

Table 6 reports *Cr* for RC and masonry school buildings of the data set grouped according to the recorded *PGA* during the two main events (i.e. $PGA_{Oct30} > PGA_{Aug24}$ or $PGA_{Oct30} \leq PGA_{Aug24}$). In particular, in order to analyse the variation of *Cr* induced by the seismic sequence, the buildings have also been grouped taking into account if they changed or not the usability rating. Therefore, buildings classified with A (B-C) usability rating after the 24 August shock have been divided into three (two) categories: A (B-C) for buildings confirming usability rating after the October seismic event, A to B-C or A to E (B-C to E) for buildings changing usability rating after the October seismic event. Table 6 shows that average *Cr* ranges between a minimum of 9% (12%) and a maximum of 33% (32%) for RC and masonry buildings, respectively.

For RC and masonry buildings that experienced $PGA_{Oct30} > PGA_{Aug24}$, Table 6 shows that the average increase of *Cr* due to the seismic sequence, Δ*Cr,* was lower than 3% for buildings that confirmed the usability rating after the event of 30 October. In particular, for B-C rating buildings the seismic sequence led to a slight damage increase and to a relevant repair cost increase (i.e. Δ*Cr* = 1 and Δ*Cr* = 3% for RC and masonry structures, respectively), while no *Cr* increase was found on A rating buildings. The increase of *Cr* was remarkable for buildings becoming unusable due to the seismic sequence. The increase of *Cr,* attained a maximum of +10 and +14% for RC and masonry structures; the maximum increase corresponds to a final usability rating E.

For RC and masonry buildings that experienced $PGA_{Oct30} \leq PGA_{Aug24,}$ Table 6, the seismic sequence only affected the repair costs of buildings that changed the usability rating after the second event. The increase of *Cr,* attained a maximum of +13 and +4% for RC and masonry structures, respectively. This data shows that, especially for RC buildings, a new seismic event,

Table 6 - Building Repair Cost Ratio of RC and masonry school buildings inspected both after the 24 August and the 30 October seismic events in each usability rating and structural type.

| Structural type | Usability rating | $PGA_{Oct30} > PGA_{Aug24}$ | | | | $PGA_{Oct30} \leq PGA_{Aug24}$ | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | No. of buildings | Average Cr [%] | | Average ΔCr [%] | No. of buildings | Average Cr [%] | | Average ΔCr [%] |
| | | | 24 August | 30 October | | | 24 August | 30 October | |
| RC school buildings | A | 102 | 9% | 9% | **0%** | 28 | 9% | 9% | **0%** |
| | B-C | 36 | 17% | 20% | **+3%** | 2 | 30% | 30% | **0%** |
| | A to B-C | 42 | 11% | 18% | **+7%** | 3 | 14% | 19% | **+5%** |
| | A to E | 3 | 16% | 24% | **+8%** | - | - | - | - |
| | B-C to E | 6 | 23% | 33% | **+10%** | 4 | 17% | 30% | **+13%** |
| Masonry school buildings | A | 55 | 12% | 12% | **0%** | 13 | 12% | 12% | **0%** |
| | B-C | 19 | 18% | 19% | **+1%** | 8 | 18% | 18% | **0%** |
| | A to B-C | 20 | 15% | 18% | **+3%** | 4 | 16% | 20% | **+4%** |
| | A to E | 8 | 14% | 28% | **+14%** | 2 | 17% | 21% | **+4%** |
| | B-C to E | 6 | 17% | 28% | **+11%** | 2 | 31% | 32% | **+1%** |

even with a lower intensity than the previous one, may strongly affect the increase of repair costs; this may be due to the damage increase on non-structural components.

It is worth noting that the indirect economic losses induced by school closures due to unusable buildings is lacking in the present analysis. Obviously, the monetary value of social gains (i.e. loss of public service and adult education due to school closures) defies estimation but clearly adds value to the incidence of a seismic sequence. Thus, for a school building becoming unusable, the increase of economic losses related to damage has to be added to the indirect costs due to the school activity interruption.

## 8. Conclusions

The paper illustrates the effects on school buildings of the seismic sequence that struck a vast area of central Italy in the period August 2016 - January 2017. The inspections carried out on 1,514 school buildings showed that:

- at the end of the seismic sequence, RC was the most common structural type in buildings with usability rating A: 69% usable and 31% unusable (i.e. 27% B-C and 4% E rating, respectively);
- by contrast, masonry was the most common structural type in the case of buildings with usability rating E: 60% usable and 40% unusable (i.e. 28% B-C and 12% E rating, respectively);
- the usability rating distribution trend as a function of ground motion parameters showed a similar trend with respect to *PGA*, *PGV*, *PSA0.3*, and *PSA1.0.* The percentage of usable school buildings inspected after the whole seismic sequence ranged from nearly 70% to 30% with increasing intensity level. The usability rating is better correlated to *PGA*, and *PSA0.3* than to other parameters;
- the type of design (gravity load design or obsolete seismic standards, NS or S) strongly affected the usability rating of school buildings. In particular, masonry school buildings resulted more affected by the design type than RC ones: percentage increase of unusable buildings of 27 and 4% from NS to S for masonry and RC buildings, respectively.

Out of 1,514 school buildings, a data set of 363 (226 RC and 137 masonry structural types) has been analysed in order to investigate the increase of damage due to the seismic sequence and relevant repair intervention costs. The analysis showed that:

- 72% of the data set showed no change in their usability rating, even in case of significant increase (up to 3 times) of the recorded seismic intensity level. The remaining 28% of the data set, rating A or B-C during the first survey, resulted unusable with more severe damage with respect to those recorded after the October shock. In some cases, this happened also for buildings that experienced a lower *PGA* in October than that recorded in August;
- the effects of a new seismic event with lower intensity than the previous one resulted in a change of the usability rating for one out of five or four for RC and masonry buildings, respectively; in case of a new event with a higher intensity than the previous one, almost one RC building out of four and one masonry building out of three, became unusable due to an increased damage level of structural or non-structural components;
- average *Building Repair Cost Ratio, Cr,* ranged between a minimum of 9% (12%) and a maximum of 33% (32%) for RC and masonry buildings, respectively;
- school buildings located in municipalities with increasing *PGA* during a seismic sequence experienced an average variation of repair costs, $\Delta Cr$, up to +10 and +14% for RC and masonry structural types. However, also aftershocks may lead to an average variation of repair costs up to +13 and 4% for RC and masonry structural types, respectively;
- RC buildings proved more highly affected by aftershocks than masonry buildings; this may be due to the increase of damage to non-structural components;
- the indirect costs, such as the costs of temporary accommodation for school activities, due to the closure of a school building that becomes unusable, should be added to the direct losses related to the increasing damage provided by a seismic sequence.

It is worth noting that these results are closely dependent on the local context when the seismic event occurs; furthermore, the repair costs have been analysed on the basis of available data of school buildings collected by the AeDES form compiled in the post-emergency phase of the 2016 central Italy earthquake. For this reason, the results may be not strictly representative of the behaviour of school buildings over the entire national territory or of other countries.

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