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Usability and damage assessment of public buildings and churches after the 2016 Central Italy earthquake: The ReLUIS experience

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ABSTRACT: The post-earthquake inspections for the assessment of buildings' usability have a key role in the post-earthquake emergency phases. In particular, a primary importance is given to the damage and usability assessment of public buildings, which is crucial for a quick recovery of the social activity. A significant contribution in the usability evaluation of such buildings (i.e. schools, hospitals, strategic infrastructures and historical and monumental heritage buildings) and churches was given by the ReLUIS - Laboratories University Network of seismic engineering - consortium, a competence centre of the Civil Protection Department, in the post-earthquake emergency phase of the recent central Italy earthquake. The in-situ surveys were 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 seismic sequence involved four significant events: M6.0 August 24, M5.9 October 26, M6.5 October 30, and M 5.5 January 18; thus several inspections were also repeated in order to evaluate the cumulative effects of seismic actions on the damage to constructions. The results of ReLUIS activities are herein presented and discussed.

KEY WORDS: school buildings, central Italy seismic sequence, usability and damage assessment, historical and monumental heritage buildings, ReLUIS

1 INTRODUCTION

One of the main objectives of the Department of Civil Protection (DPC) in the aftermath of the earthquake is the assessment of damage on public buildings, with emphasis on school buildings, hospitals, strategic infrastructures and sites with historical and monumental heritage, and the definition of a sound strategy to quickly repair and strengthen the ones with minor structural damage only.

A significant contribution in the usability evaluation of such buildings was given by the ReLUIS - Laboratories University Network of seismic engineering - consortium, a competence centre of the Civil Protection Department, after recent Italian earthquake emergencies: L'Aquila 2009, Emilia 2012, and recently central Italy sequence 2016-2017 (Dolce et al. 2009, Di Ludovico et al. 2012, Frascadore et al. 2016, Dolce et al. 2016a,b, Di Ludovico et al. 2017a,b). Researchers from several Italian universities were involved to assess damage and usability of public structures; they were mobilized in accordance with emergency procedures in case of earthquake.

The recent central Italy earthquake resulted in thousands of buildings with structural or non-structural damage and caused severe damage to monumental heritage. Priority was in particular to churches. The assessment of the safety conditions of buildings in terms of damage and usability was carried out through inspections conducted by teams coordinated by the DPC. The teams were composed of two or three technicians of several institutions (i.e. Regions and Local Authorities, Firefighters, Engineers/Architects/Surveyors, Centers of Competence) at the request of regional administrations.

This paper focuses on the analysis of the activities carried out by ReLUIS consortium in the post-earthquake emergency phase of the recent 2016-2017 central Italy earthquake sequence. Priority was given to public buildings, primarily schools, historical and monumental heritage and churches. In particular, the paper illustrates and discusses the results of the the inspections conducted on approximately 280 school complexes, corresponding to approximately 500 school buildings. Then, the memory focuses attention on the activity carried out by ReLUIS at the preliminary assessment of the technical information necessary to establish the economic convenience of the reparability of school buildings classified as unusable at the end of the sequence. Finally, an overview of the activity of ReLUIS consortium on over 5,000 historical and monumental heritage buildings, and in particular churches, under the supervision of DPC and Italian Ministry of Heritage and Cultural Activity and Tourism (MiBACT), is herein presented.

A detailed discussion on the most frequent observed damage types on structural and/or non-structural elements of masonry and Reinforced Concrete (RC) school buildings is

reported in Di Ludovico et al., 2017c. Remarks on damage and response of school buildings inspected all over the four regions is reported in Di Ludovico et al., 2017d.

2 RELUIS: DAMAGE AND USABILITY ASSESSMENT OF SCHOOLS

In the post-earthquake emergency phase of the central Italy seismic sequence, the total amount of surveys carried out by experts of several institutions involved 1,514 school structures (buildings and sports facilities of pre-primary, primary, high schools and universities) in four regions of central Italy: Abruzzo, Lazio, Marche, and Umbria. The AeDES "Building Operability and Damage during the Post-Earthquake Emergency" survey form (Baggio et al. 2007), whose most recent official version can be found in (D.P.C.M. 14.01.2015), was used to evaluate the safety conditions of buildings in order to enable people to return to their social and economic activities. The AeDES survey form is a first level survey filled on the basis of visual in-situ inspection of the building. The form also collects data on the geometrical and qualitative characteristics - including height, plan and elevation configurations, age, type of vertical and horizontal structures, type of foundation and roof - and whether the building had been retrofitted. It allowed buildings to be classified into the main following 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. At the end of the seismic sequence, 2,043 AeDES survey forms were filled (Di Ludovico et al. 2017c). Indeed, in several cases, school buildings structures were re-inspected after a new major seismic event. The seismic sequence involved four significant events: M=6.0 August 24, M=5.9 October 26, M=6.5 October 30, and M=5.5 January 18. Table 1 shows the number of structures inspected after each event of the seismic sequence as well as that of structures already inspected in the previous events. Table 1 shows that 1445 different school buildings (about 95%) were inspected in the aftermath of two main shocks of the sequence, namely August 24, 2016 (i.e. 872 buildings) and October 30, 2016 (i.e. 573 buildings never inspected before).

Table 1. Number of school structures inspected after the four seismic events.

No. 872 school structures inspected after Aug 24	
after Aug 24	872
No. 92 school structures inspected after Oct 26	
already inspected after Aug 24	36
after Oct 26	56
No. 1,012 school structures inspected after Oct 30	
already inspected after Aug 24	400
already inspected after Oct 26	16
already inspected both after Aug 24 and after Oct 26	23
after Oct 30	573
No. 67 school structures inspected after Jan 18	
already inspected after Aug 24	11
already inspected after Oct 26	1
already inspected after Oct 30	15
already inspected both after Aug 24 and after Oct 26	-
already inspected both after Aug 24 and after Oct 30	18
already inspected both after Aug 26 and Oct 30	1
already inspected after each previous event	8
inspected after Jan 18	13

Table 2 reports the number of school buildings inspected in each region after the entire seismic sequence, as well as the number of structures classified as usable (i.e. A rating) or unusable (i.e. B/C usability rating for buildings/structures with limited or no structural damage, but with severe non-structural damage, and E usability rating for those with high structural or non-structural risk, high external or geotechnical risk, respectively) according to the AeDES form. In terms of usability assessment, about 67% of the school structures were assessed with usability rating A (1,375 buildings with no significant damage), and the remaining 33% were assessed as unusable (546 buildings, 27% of dataset, rating B/C, and 122 buildings, 6% of dataset, rating E, respectively).

Out of 2,043 inspections on school buildings, 474 (i.e. 23%) corresponding to 282 school complexes, were carried out by teams of surveyors made up of experts from a list of ReLUIS researchers. Following the M6.0 August 24, 2016 shock, the activity of ReLUIS consortium started on 29 August 2016, under the supervision of DPC at second floor of DiComaC (Direction of Command and Control), located at Largo Graziosi, Rieti, Italy. The usability assessment of schools and public buildings were carried out from August 29 to September 21 in an area near the borders of the Umbria, Lazio, Abruzzo and Marche regions. They involved surveys on 160 schools complex, for a total of 253 structures, and 47 public buildings, for a total of 54 structures. In the aftermath of October 2016 seismic events (M5.9 and M6.5, respectively), surveys were carried out from November 3 to November 28 on 122 schools complex, for a total of 221 structures, and 82 public buildings. In particular, 26 school buildings, for a total of 57 structures, were inspected in Abruzzo region and 96 school buildings, for a total of 163 structures, all over the Marche region, and 1 school building in Umbria.

Table 3 reports the number of school buildings inspected by ReLUIS technicians in each region after the entire seismic sequence, as well as the number of structures classified as usable (i.e. A rating) or unusable (i.e. B/C usability rating for buildings/structures with limited or no structural damage, but with severe non-structural damage, and E usability rating for those with high structural or non-structural risk, high external or geotechnical risk, respectively) according to the AeDES form. In terms of usability assessment, about 70% of the school structures were assessed with usability rating A (330 buildings with no significant damage), and the remaining 30% were assessed as unusable (102 buildings, 21% of dataset, rating B/C, and 42 buildings, 9% of dataset, rating E, respectively).

Table 2. Number of inspected school buildings in each region and number of structures classified as usable or unusable after the entire seismic sequence of central Italy.

Region	A	B/C	E	Total
Abruzzo	329	116	30	**475**
Lazio	232	72	13	**317**
Marche	630	248	67	**945**
Umbria	184	110	12	**306**
Total	1375	546	122	**2,043**

Table 3. Number of school buildings inspected by ReLUIS in each region and number of structures classified as usable or unusable after the entire seismic sequence of central Italy.

Region	A	B/C	E	Total
Abruzzo	143	38	17	**198**
Lazio	67	9	2	**78**
Marche	118	48	22	**188**
Umbria	2	7	1	**10**
Total	**330**	**102**	**42**	**474**

3 RELUIS: REPAIRABILITY ASSESSMENT OF UNUSABLE SCHOOLS

Starting from December 6, 2016, ReLUIS carried out additional activities to support the DPC and the Delegation Commissioner for Reconstruction, aimed at the preliminary assessment of the technical information necessary to establish the economic convenience of the reparability of the 122 school buildings classified as unusable (E rating of AeDES survey form) following the earthquakes of 24 August, 26 and 30 October. The activity involved 8 ReLUIS Research Units made of 98 experts in the field of seismic risk. The activities were articulated as follows:

a) inspection of each unusable school complex;
b) finding of any available documentation (geometric survey of the building, original structural design, technical calculations related to structural interventions carried out over time, seismic assessment of the structure, project documentation of planned interventions but not yet realized);
c) drafting of the technical report with the evaluation of:

– damage grade, expressed on a scale consisting of four levels (from 1 to 4);
– vulnerability of the structure, expressed on a scale consisting of three levels (low, medium, high).

Note that out of a total of 122 school buildings classified as unusable after the entire 2016 seismic sequence, the additional inspections were carried out on only 90 buildings (66 school complexes): 14 in Abruzzo (11 school complexes), 7 in Lazio (7 school complexes), 56 in the Marche region (36 school complexes), 13 in Umbria (12 school complexes). In particular, for 32 school buildings it was not necessary to carry out the assessment of reparability due to several reasons including: demolition orders; abandoned facilities; seized structures; pre-existing unusability; etc.

3.1 *School buildings dataset*

The number of buildings in each structural type related to different construction age periods and number of storeys as well as their cumulative percentages are presented in Figure 1a,b. Out of 90 inspected unusable school buildings under investigation, 37% concerns RC buildings, 54% masonry buildings, while the remaining 9% involves buildings with a mixed structural type (i.e. comprising RC and masonry structural members), steel structure or other types.

Figure 1a,b shows that 82% of the RC building dataset (corresponding to 27 buildings) have a number of storeys less than 4. The number of RC buildings starts to be significant in

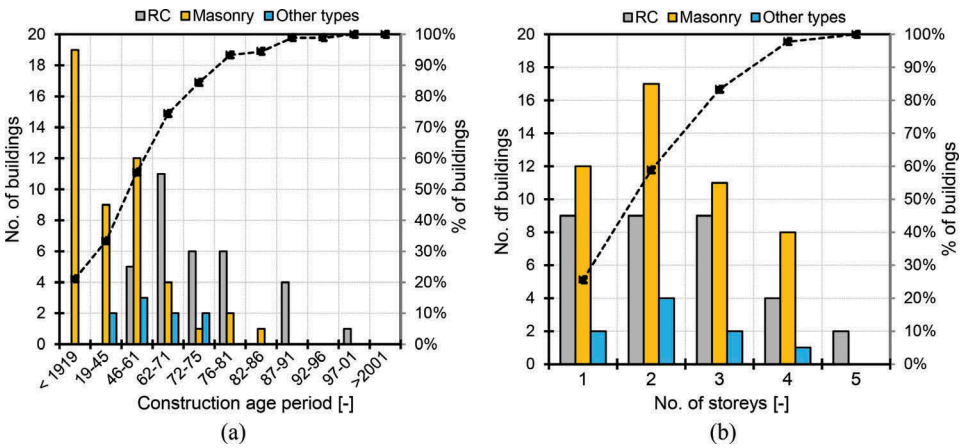

Figure 1. Unusable school buildings in each the structural type: construction age period (a) and number of storeys (b).

periods after 1961 (see Figure 4b), with peaks of 11 buildings in 1962-1971 (corresponding to 33% of the RC building dataset). By contrast, Figure 1a,b shows that the number of masonry buildings is almost the same for periods before 1972-1975, while no buildings inspected for periods after 1971. Most of the masonry buildings have a number of storeys between 1 and 3 (40 buildings corresponding to 83% of the masonry building dataset).

3.2 *Damage grade, vulnerability and operational level*

According to the agreement with the DPC and the Delegation Commissioner for Reconstruction, for each school complex the assessment of reparability was carried out in accordance with Ordinance no. 14 of 14 February 2013 (O.P.C.M. No. 14 of 14/02/2013) issued by the Emilia Romagna Region following the seismic events of May 2012. The ordinance allows the establishment of the operational level of buildings that suffered heavy damage as a function of the damage grade and the vulnerability; this in order to evaluate the reparability.

Table 4 summarizes the criteria for defining the damage grade, the vulnerability and the operational level of buildings according to O.P.C.M. No. 14 of 14/02/2013. In particular, for each building the damage grade, the vulnerability and the operational level were defined as follows:

- the "damage grade" was expressed on a scale consisting of 4 grades (from 1 to 4), as indicated in Table 4. It was derived from the "damage thresholds" referred to in Tables 1.1, 1.2 and 1.3 of the aforementioned Ordinance, depending on the structural type (RC, masonry or mixed structure);
- the "vulnerability" was expressed on a scale consisting of 3 levels (low, medium, high), as indicated in Table 4. It was derived from the "degree of deficiencies" represented in Tables 2.1, 2.2, 2.3 and 2.4 of the aforementioned Ordinance, and the "acceleration factor" in Table 2.5 of the Ordinance.
- the "operational level" obtained from the combination of damage and vulnerability. It was expressed on a scale consisting of 5 levels (B-C, E_0, E_1, E_2, E_3), as indicated in Table 4. The level B-C and E_0 correspond to a state of damage between 1 and 2 with medium-low vulnerability and identify the so-called light reconstruction [O.P.C.M. n. 51 of 5/10/2012 and O.P.C.M. n. 73 of 20/11/2014]. The operational levels E_1, E_2 or E_3, are connected to the different states of damage and vulnerability above the pre-established threshold for "light E" reconstruction. In detail for buildings characterized by an operating level E_1 or E_2, earthquake repair and improvement interventions are planned in order to reduce seismic vulnerability and increase safety to a level of at least 60% of that required for new

Table 4. Definition of the "damage grade", "vulnerability" and "operational level" according to Ordinance no. 14 of February 14th 2013 Emilia Romagna Region.

	Damage grade 1	*Damage grade 2*	*Damage grade 3*	*Damage grade 4*
Low vulnerability	B-C	B-C	E_0	E_2
Medium vulnerability	B-C	E_0	E_1	E_3
High vulnerability	B-C	E_1	E_2	E_3
Damage grade 1 : *damage lower than "significant damage"*				
Damage grade 2 : *damage higher than "significant damage" and lower than "heavy damage"*				
Damage grade 3 : *damage higher than "heavy damage" and lower than "very heavy damage"*				
Damage grade 4 : *damage higher than "very heavy damage"*				
Low vulnerability: acceleration factor higher than 0.5 and "low grade of deficiencies"				
Medium vulnerability: other cases classified neither as *Low Vulnerability* nor *High Vulnerability*				
High vulnerability: acceleration factor lower than 0.3 and "high grade of deficiencies"				

buildings; for buildings with an operational level E3, earthquake repair and adaptation of the entire building or demolition and subsequent reconstruction are planned.

A parametric cost is associated with each operating level as shown in Table 5 [O.P.C.M. n. 14 of 14/02/2013].

Figures 2a-c report the distribution of damage grade (Figure 2a), vulnerability (Figure 2b) and operating level (Figure 2c) of the unusable school buildings in each structural type (i.e. RC and masonry). Figure 2a shows that about 83% of the examined buildings were characterized by damage grade between 1 and 2. Figure 2b also shows that about 68% of the buildings were classified in the medium vulnerability category. Figure 2c shows that about 69% of the buildings are characterized by an operating level between B-C and E0, corresponding to a damage grade lower than the "very heavy" damage and a “medium-low” vulnerability.

Table 5. Definition of parametric costs for the different "operating levels".

Parametric cost	Operational Level E_1	Operational Level E_2	Operational Level E_3	Operational Level E_0
Lower than 120 mq	1000	1250	1450	800
Higher than 120 mq and lower than 200 mq	800	1000	1200	650
Higher than 200 mq	700	850	1000	550

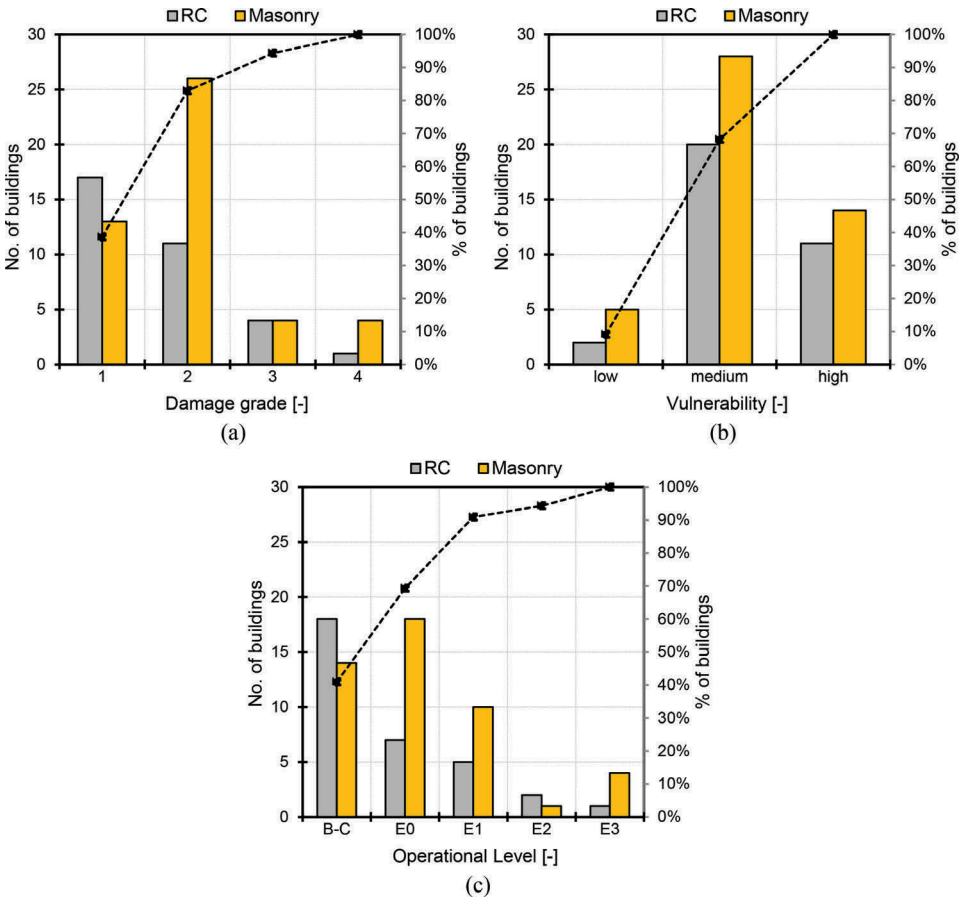

Figure 2. Damage grade (a), Vulnerability (b) and Operational Level (c) of unusable school buildings.

4 HISTORICAL AND MONUMENTAL HERITAGE BUILDINGS

The activity of ReLUIS consortium on historical and monumental heritage buildings, and in particular churches, started on 13 September 2016, under the supervision of DPC and Italian Ministry of Heritage and Cultural Activity and Tourism (MiBACT). Damage survey of such buildings was carried out using the forms provided by the Civil Protection (Working group of Cultural heritage – GLABEC) respectively for churches (Model A-DC 2006) and for buildings (Model B-DP 2006). Both the forms were proposed by the National Group for Defense Against Earthquakes (CNR-GNDT), the National Seismic Service (SSN) of the Department of Civil Protection (DPC) and the University of Genova (PCM DPC 2011), and approved with the Law Decree DPCM of 23 February 2006, (DPCM 2006).

In particular, the "Damage survey form for the Cultural Heritage – Churches" (Model A-DC 2006) adopted during the assessment of churches and provides data on:

- general information about the building (address, owner and building manager contacts, typology, dimensions, construction materials, etc.);
- macroelements identification;
- damage and vulnerability assessment;
- use and access restriction;
- securing intervention.

Use and access restriction is deemed using the following classification (PCM DPC 2011): safe; unsafe; partially safe with safe and unsafe zones being identified within the building. The unsafe part must not compromise the structural stability of the safe parts and the safety of inhabitants; safe with precautions. The access and use of the building is not allowed until securing interventions are provided in a limited amount of time; temporarily unsafe. The access and use is suspended due to difficulties occurred during the surveys or the opinion of other technicians is required (i.e. geologists); unsafe due to external causes. The safe use of the building is compromised by nearby unsafe buildings, structures or other risks.

The usability assessment of monumental and historical buildings and churches were carried out from September 13 to October 27, 2016, on 339 historical and monumental heritage buildings in Abruzzo, 115 in the Lazio Region, 277 in Umbria and 301 in the Marche region, for a total of 1,032 surveys. Then, surveys on historical and monumental heritage buildings were carried out from November 15, 2016, to January 18, 2017, and from January 18 to March 24, 2017, on a total of 495 and 3,598 surveys, respectively, all over the four regions.

5 CONCLUSIONS

The ReLUIS consortium has been strongly involved in the aftermath of the 2016-2017 central Italy earthquake sequence. ReLUIS support to DPC consisted of technical surveys of public buildings (i.e. schools, hospitals, strategic infrastructures and historical and monumental heritage buildings) and churches.

Priority was given to the damage and usability assessment of schools, which play a critical role for social and cultural life of a community. The total amount of surveys carried out by ReLUIS technicians involved 253 out of 874 school structures after August 24, and 221 out of 1,015 school structures after October 26-30. At the end of the seismic sequence, 67% of schools resulted usable and 33% unusable (i.e. 27% B/C and 6% E rating, respectively). To establish the economic convenience of the reparability of the 122 school buildings classified as unusable (E rating of AeDES survey form) following the earthquakes of 24 August, 26 and 30 October, additional activities were carried out by ReLUIS teams for a total of 90 school structures (i.e. 66 school complexes). For each school complex, the assessment of damage grade, vulnerability and operational level was carried out in accordance with Ordinance no. 14 of 14 February 2013 issued by the Emilia Romagna Region. The analysis of the examined buildings shows that in most cases unusable schools were characterized by a damage grade lower than the "very heavy" damage and by a "medium-low" vulnerability. This activity provided preliminary

but significant information on the main vulnerabilities of school buildings. This can be a starting point for defining intervention strategies and priorities aiming at strongly reducing the seismic risk of school buildings.

In the aftermath of the M6.0 August 24, 2016 shock, several ReLUIS teams were further involved in field to survey damaged heritage buildings. They role was to fill edited survey forms (Model A-DC and Model B-DP 2006) and give directions to make the buildings safe using simple, effective, removable and fast in installation shoring systems. A total of 1,032 surveys, from September 13 to October 27, and a total of 495 and 3,598 surveys, from November 15, 2016, to January 18, 2017, and from January 18 to March 24, 2017, respectively, were carried out all over the four regions hit by the earthquakes. Data collected during the post-earthquake building assessments are particularly useful to identify the mechanisms of collapse activated and the most encountered vulnerabilities. The goal is to analyse the seismic behaviour of different building typologies and propose suitable improvement techniques that reduce the risk and the fatalities during future earthquake events.

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