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DAMAGE ASSESSMENT AND REPAIR COSTS OF RESIDENTIAL AND SCHOOL BUILDINGS AFTER RECENT ITALIAN EARTHQUAKES

M. Di Ludovico[(1)], C. Del Vecchio[(2)], A. Prota[(3)]

[(1)] *Associate Professor, Dept. of Structures for Engineering and Architecture, University of Napoli Federico II, diludovi@unina.it*
[(2)] *Assist. Professor, Dept. of Engineering, University of Sannio, Benevento, cdelvecchio @unisannio.it*
[(3)] *Full Professor, Dept. of Structures for Engineering and Architecture, University of Napoli Federico II, aprota@unina.it*

Abstract

In the aftermath of the recent Italian earthquakes, in-situ surveys performed by skilled engineers allowed to collect and classify the earthquake damage to buildings and infrastructures. Furthermore, the monitoring of the reconstruction processes allowed collecting unique data on the actual cost related to the repair and retrofit of private and public buildings at regional scale. These data are of paramount importance for the calibration and validation of vulnerability and consequence functions useful for the development of reliable loss scenarios and risk maps. Although great advances were made in the development of fragility functions and consequence functions at system or component level for residential buildings, further research effort should focus on the post-earthquake response of school buildings. Indeed the differences in the structural systems, non-structural components, and contents features might significantly change the performance requirements and the expected losses.

This study deals with the post-earthquake response of reinforced concrete buildings by using observational data. The damage and repair costs experienced by residential buildings due to the 2009 L'Aquila earthquake are discussed at building and component level. Reliable consequence functions to be used in available loss-assessment procedures are proposed. The seismic response of school buildings is also investigated by using available data. The damage at building level is assessed and the seismic vulnerability of different building classes is discussed. The actual repair and retrofit costs are obtained from cost estimates approved in the reconstruction process. A comparison between the seismic performances of residential and school buildings is performed in terms of observed damage and repair/retrofit costs.

Keywords: loss-assessment; post-earthquake; RC buildings; school; vulnerability.

1. Introduction

Recent devastating earthquakes showed the high vulnerability of existing RC buildings designed with old code provisions and without proper seismic details. Lack of transverse reinforcements and capacity design rules have found to significantly limit the seismic response of existing RC buildings often resulting in premature failures. Although the seismic performance of structural system plays a crucial role in the life safety of the occupants, the seismic performance of non-structural components significantly affect the global damage state of the building and the repair costs [1,2]. Post-earthquake observations outlined that the role of such components in the definition of the global damage state of the building [2,3] (see Fig. 1). This aspect is even more critical for public buildings where the performance requirements can be more restrictive than residential buildings [4].

The damage surveys in the aftermath of recent seismic events worldwide outlined that the seismic response of non-structural components is even more critical for the stock of reinforced concrete (RC) buildings with hollow clay brick infill walls. Indeed, the brittle behaviour of such components commonly lead to a premature shear cracking or out-of-plane failure when subjected to moderate intensity seismic events. Their response often characterizes the global damage state of the entire building as commonly showed in the post-earthquake damage surveys [2,3,5]. Furthermore, a moderate-to-slight damage to such components, may have a significant influence on the repair costs. As deeply investigated in Del Vecchio et al. [2], the repair cost of such components is in the order of 50% of the total building repair cost. This cost rise up to the 80% when the repair cost of windows/doors and plumbing/electrical system is considered together with the repair cost of infills and partitions. Since that, the response of such components depends by number of variables, their seismic response is very difficult to predict. In this context, observational data can be of paramount importance in order to calibrate/validate reliable fragility and loss functions for RC buildings typical of the Mediterranean area [2,6,7]. These data can be used to conduct reliable vulnerability and loss assessment at building level or at regional scale that is a primary target of the modern seismic engineering [8].

The reconstruction process followed to the L'Aquila earthquake (2009) was a unique opportunity to collect data on reconstruction costs on a large scale. The Italian government supported the reconstruction process, guaranteeing public funding for the repair and strengthening of damaged residential and public buildings [9]. Detailed descriptions of the reconstruction policy, relevant regulations, and an overview of the data related to the reconstruction of 5,775 residential buildings damaged by the earthquake are reported in Di Ludovico et al. [5,10].

These data have been widely investigated in recent [5,10], with statistics reported on building populations, earthquake damage, and repair and retrofit costs at the building level. They have also been used to calibrate simplified [7] and refined consequence functions and to validate available refined or simplified loss-assessment methodologies for the European context [2,6].

Although great effort was dedicated to the analysis of the seismic response of RC building by using post-earthquake data, the majority of the studies focused on residential buildings. Minor attention has been dedicated to post-earthquake response of public buildings [4,11]. Strategic buildings, schools, hospitals and offices have a crucial role in the emergency management and recovery of earthquake stricken communities. The accurate prediction of their seismic performance is crucial to develop loss-assessment scenarios and activate effective risk mitigation plans. Indeed the differences in the structural systems, non-structural components, and contents might significantly change their performance requirements.

This papers deals with the seismic response of RC buildings based on the observational data collected in the aftermath of the 2009 L'Aquila earthquake. A large database of residential and school buildings is considered focusing on the municipalities that experienced macro-seismic intensity. A first comparison between the observed response of RC residential and school buildings is presented and discussed in terms of the damaged components and the achieved damage state. Finally a comparison between the reconstruction costs of residential and school building is proposed and the results are discussed.

Fig. 1 – Damage to existing RC school building due to recent Italian earthquakes: out-of-plane damage and collapse of infills (a)(b) (c); damage to ceilings (d); damage to floor and partitions (e); collapsed school building during the 2016 Central Italy earthquake (f).

2. The L'Aquila 2009 earthquake

In the 2009 a Mw 6.3 earthquake hit the Abruzzo region with epicentre within the municipality of L'Aquila (see Fig. 2). The earthquake resulted significant damage to residential, public buildings and infrastructures leading to hundreds of victims and thousands of injuries. The assessment of damage and usability of buildings started in the immediate aftermath of the event and it was coordinated by the Italian Civil Protection Department [12]. The AeDES form, a first level survey form for post-earthquake damage and usability assessment, was adopted as a rapid tool to evaluate the conditions of the buildings [13]. The reconstruction process started few months after the emergency phase and it was supported by the Italian government, guaranteeing public funding for the repair and strengthening of damaged buildings. Detailed descriptions of the reconstruction policy, relevant regulations, and an overview of the data related to the reconstruction of 5,775 residential buildings damaged by the earthquake are reported in Di Ludovico et al. [5,10]. A team of administrative, technical and financial experts was set to check the documents for funding application. This was an unique opportunity to collect data on damage and reconstruction costs at large scale resulting in the ReLUIS database.

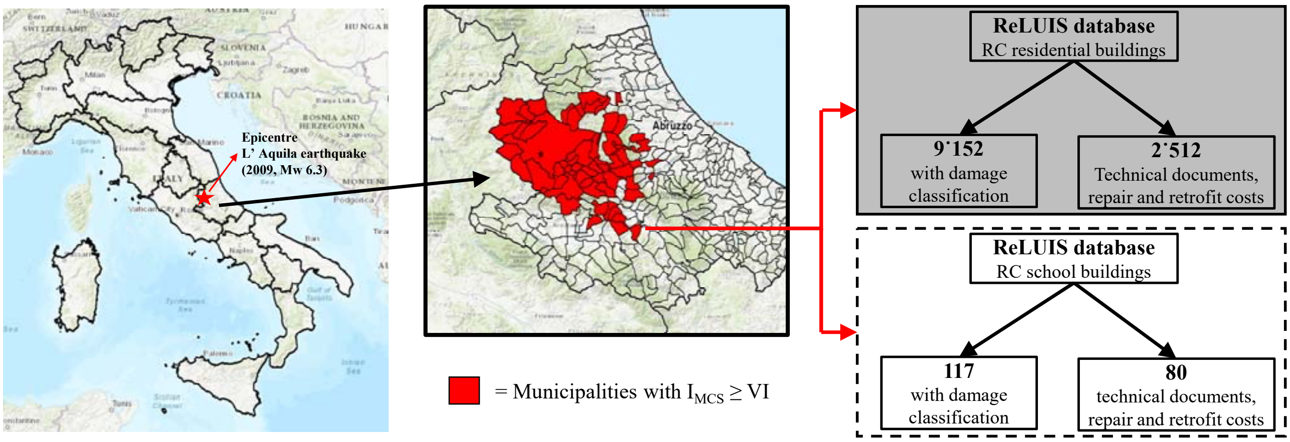

Fig. 2 – The epicenter of the 2009 L'Aquila earthquake and a closeup on the Abruzzo region.

The Abruzzo region had more about 350.000 buildings [14] and about 1300 schools [15]. About 10.000 out of the 100.000 RC buildings were inspected and a damage classification is available. However, it worth mentioning that the full database cannot be used in order to avoid to introduce bias in the damage analysis [16] and the buildings in the municipalities with low completeness ratio are discarded. In this study, only the municipalities with a macro-seismic intensity (I_{MCS}) higher then VI are considered (see Fig. 2) for the preliminary damage analysis. In these municipalities, at that time there were 181 school buildings. 117 RC school buildings were surveyed and a damage classification is available. Furthermore, in order to conduct an analysis of the reconstruction costs, 2512 RC buildings were collected from the ReLUIS database of technical and financial documents. On the other side, the special office for reconstruction of the municipalities of the seismic crater (USRC) provided the technical and financial documents for 80 RC school buildings.

3. Database of RC buildings

The database of RC residential and school buildings provided data on the main building characteristics and earthquake damage at building and component level. Fig. 3 shows the frequency and cumulative distributions of the buildings in terms of construction age (Fig. 3a), number of storeys (Fig. 3b) and average surface area (Fig. 3b) for both the residential and school buildings.

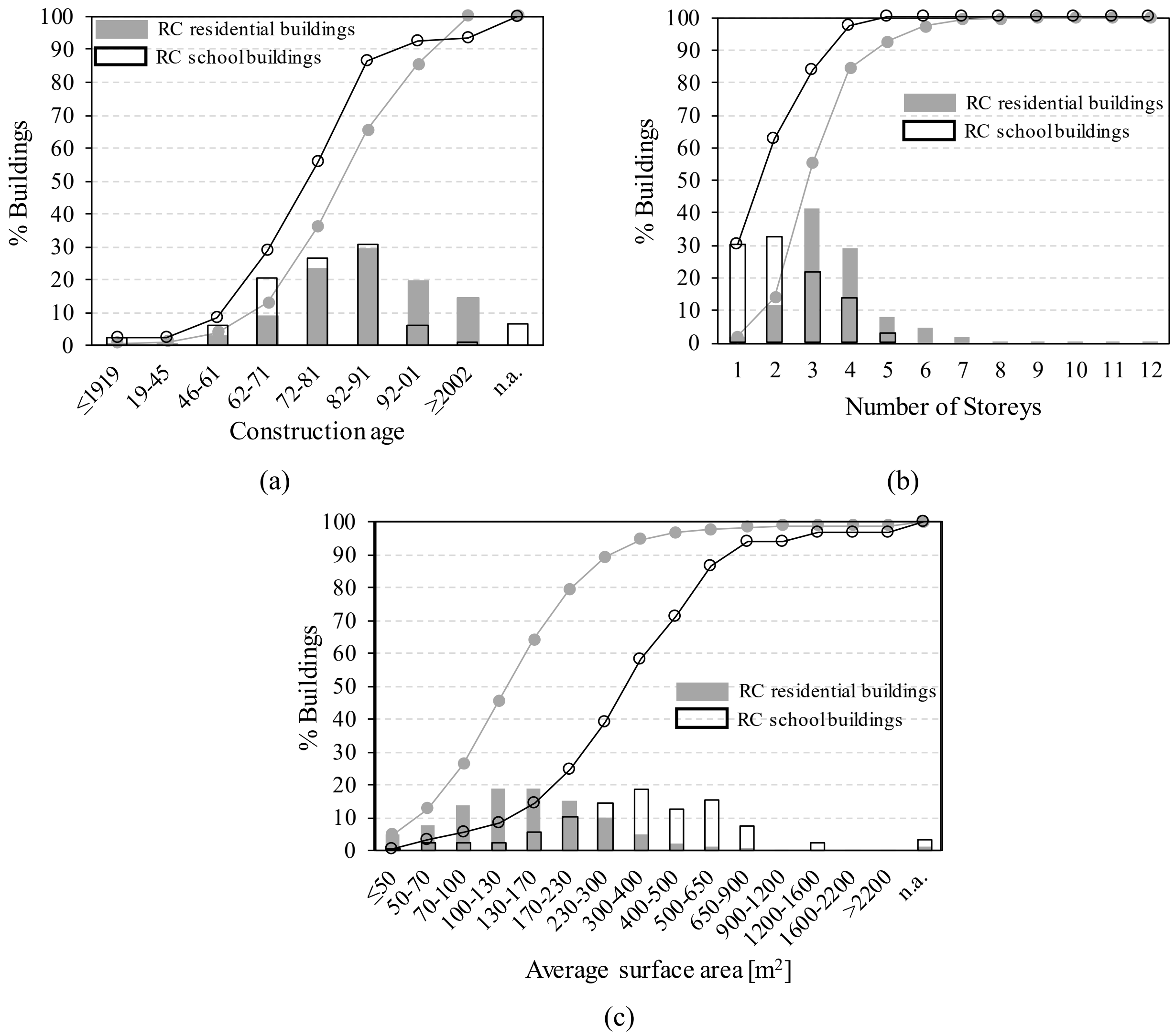

Fig. 3 – Comparison in terms of percentage and cumulative distributions between RC residential and school buildings in terms of: (a) construction age; (b) number of storeys; (c) average surface area.

The comparison outlines that the majority of the buildings were built before the 1991. It is worth remembering that the first code prescription implementing the capacity design approach and suggesting proper seismic detailing for RC buildings were introduced in Italy in the 1997 [17]. Thus, most of the buildings may have lack of proper seismic detailing. Furthermore, the school building stock is older than that of residential buildings. The analysis of the number of floors outlines a significant difference between existing school building (about the 80% have less than 3 floors) and residential buildings (where the majority have more than 3 floors). The difference between residential and school buildings are even more relevant in terms of average surface area. This reflects the Italian architectural design practice of RC school building commonly with low number of floors and high in-plan surface. The latter two parameters may have a significant influence on the reconstruction costs since they are commonly normalized for the total surface area.

4. Analysis of the earthquake damage

The AeDES form [13] is commonly used in Italy for the post-earthquake in-situ damage surveys. It allows to assign an usability rating based on the detailed damage detection to structural and non-structural components. A detailed description of the distribution of the usability ratings for residential buildings and the correlation with reconstruction costs is reported in Di Ludovico et al. [5,10]. In this paper, the damage at component level reported in the section 4 of the AeDES form (see Fig. 4) is analyzed. This section allows to collect detailed information on the damage severity (D1 Slight, D2-D3 Medium-severe, D4-D5 Very high) and damage extent (<1/3, 1/3-2/3, >2/3) to building structural and non-structural components (i.e. infills and partitions). An overview of the typical damage experienced by school buildings is reported in Fig. 4.

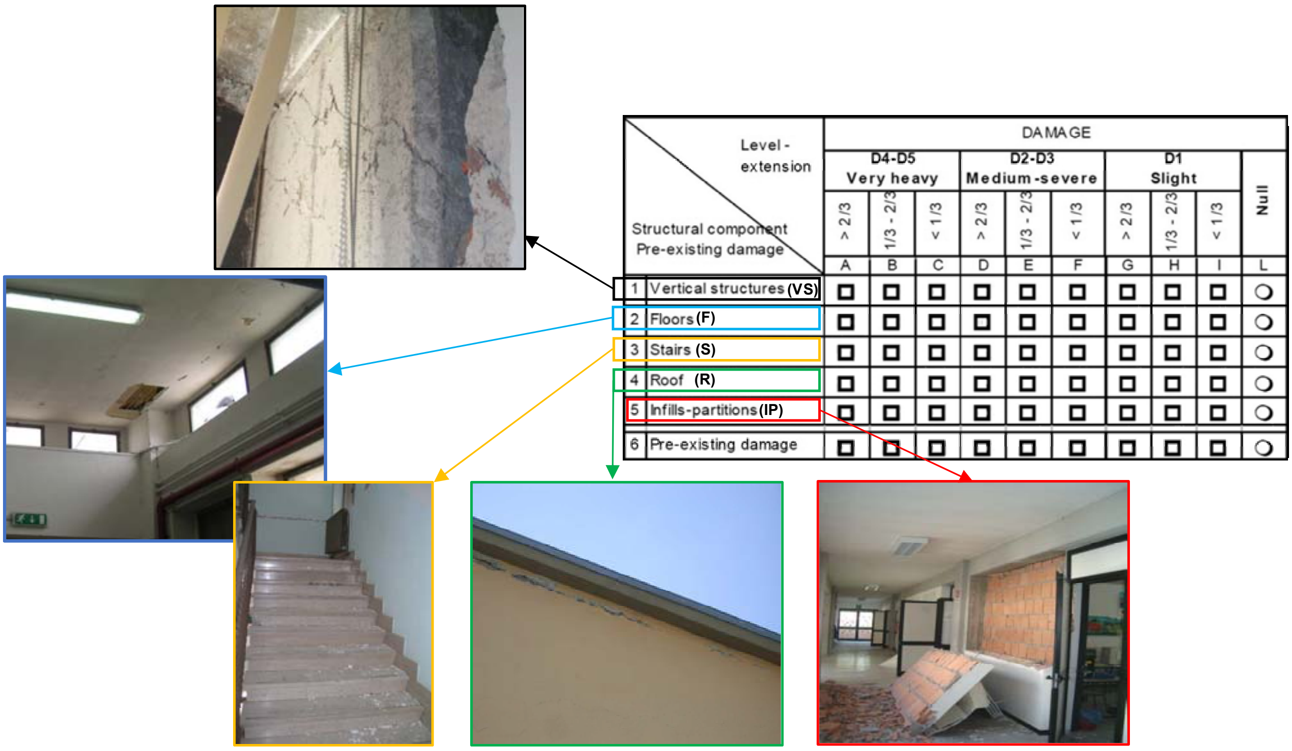

Fig. 4 – The AeDES form for post-earthquake damage surveys and typical damage to RC school buildings.

A first analysis of the damage and a comparison between the performance of residential and school buildings is reported in Fig. 5. It shows the percentage distribution of damage to the most damaged c Inomponents (i.e. Vertical Structures “VS”, Infills-partitions “IP”) as function of the damage severity. The majority of the detected earthquake damage consists in the damage of infills and partitions, IP. Moving from slight damage, D1, to very heavy damage, D4-D5 the percentage of the damage to vertical structures increase significantly and in turn the percentage damage to IPs decreases. This well reflects the performance of infilled existing RC buildings during recent earthquakes showing the significant damage to such brittle non-structural components. Minor differences can be observed between the residential and school buildings. In particular, the school buildings showed less damage to VS than to IP if compared to the residential buildings.

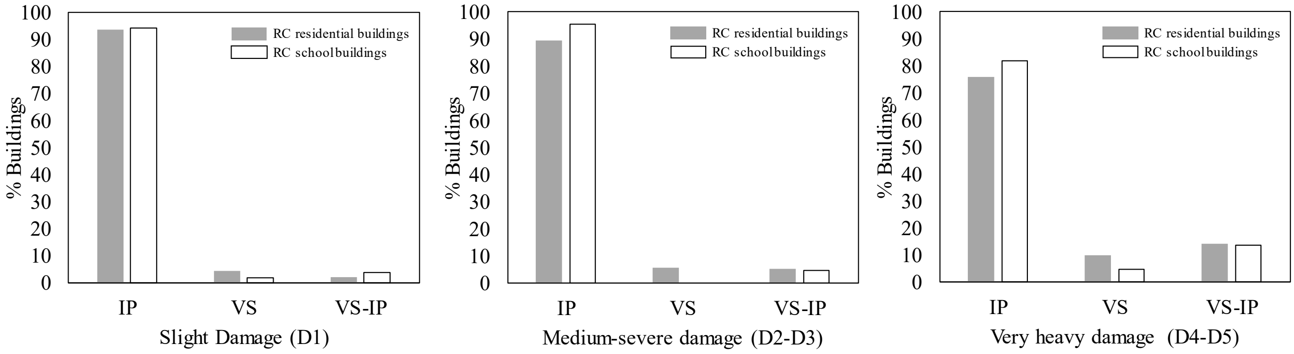

Fig. 5 – Distribution of the earthquake damage to the building components for each damage levels.

In order to compare the global performance of the RC buildings available in the database, the damage to the different building components should be converted into a damage state (DS). Different methodologies for the classification of the DS using the observed earthquake damage reported in the AeDES forms [13] are available. The classification proposed by Del Gaudio et al. [16] is used in this study. According to the widely recognized European Macroseismic Scale EMS-98 [18], this classification defines the damage state as a function of the maximum damage experienced by the vertical structures and IPs. Apart from DS0 (null damage), five DSs are identified: DS1 (Negligible-to-slight damage, consisting of fine cracking in the plaster or the IPs); DS2 (moderate damage, consisting of cracking in the structural members and IPs); DS3 (substantial-to-heavy damage, consisting of extensive cracking of structural members and large cracks or the failure of IPs); DS4 (very heavy damage, consisting of large cracks in structural members or collapse of a few members); and DS5 (destruction, consisting of the collapse of the ground floor or other portions of a building). A comparison of the damage state experienced by residential and school building of the selected database is reported in Fig. 6.

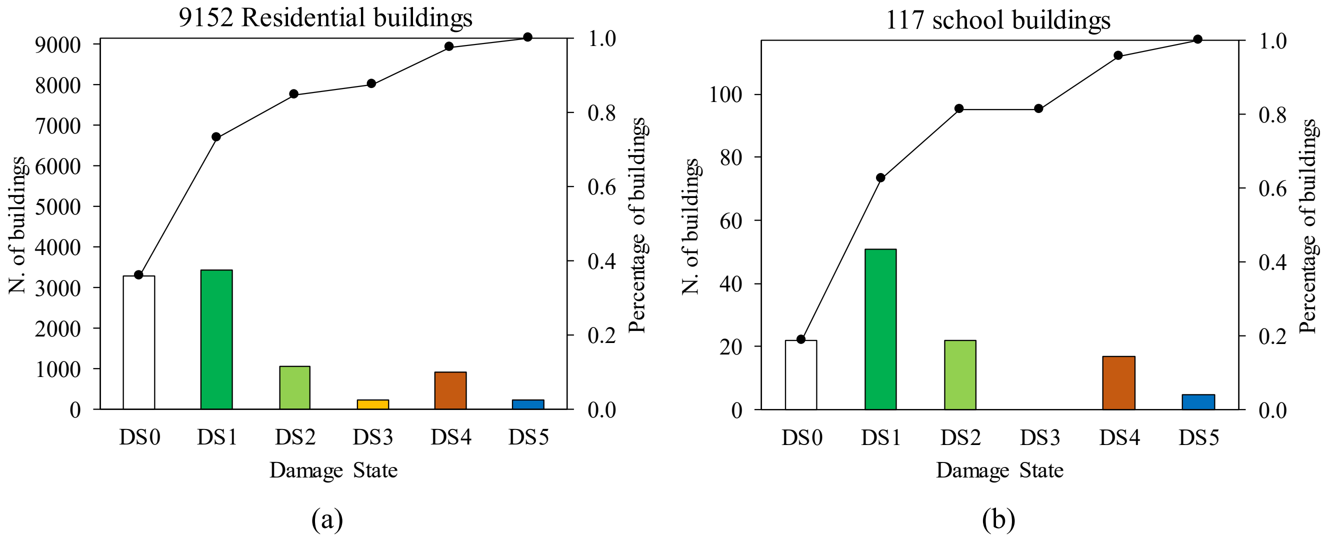

Fig. 6 – Comparison in terms of the achieved damage state between the RC residential buildings (a) and RC school buildings.

The comparison outlines a similar seismic response of the residential (Fig. 6a) and school buildings (Fig. 6b) and minor differences can be observed. In particular, based on this preliminary analysis, the residential buildings showed a rate of undamaged buildings (DS0) higher than schools. It is worth mentioning that, at this stage of the data collection, the completeness ratio of the surveys on residential building is higher than the one on school buildings and further effort is needed to investigate this aspect. A similar trend can be observed for the other DSs where the school building shows a damage slightly higher than residential ones.

In order to investigate on the correlation of the earthquake damage and the measured peak ground acceleration (PGA) the selected buildings were georeferenced by using a GIS application and the comparison with the ShakeMap of the April 6, 2009 provided by the INGV (Italian National Institute of Geophysics and Volcanology) allowed to obtain the a prediction of the PGA at the site of each building. Due to lack of a proper amount of data for the school buildings, only two ranges of PGA can be considered. The two ranges considered in this study are PGA<0.3 g and PGA ≥ 0.3g, where the 0.3 g is the reference PGA at the life safety limit state (LSLS) for the desing of new school buildings with T_R=712 years. The results in terms of cumulative damage experienced by the dataset of residential and school building in the two ranges of PGA are reported in Fig. 6.

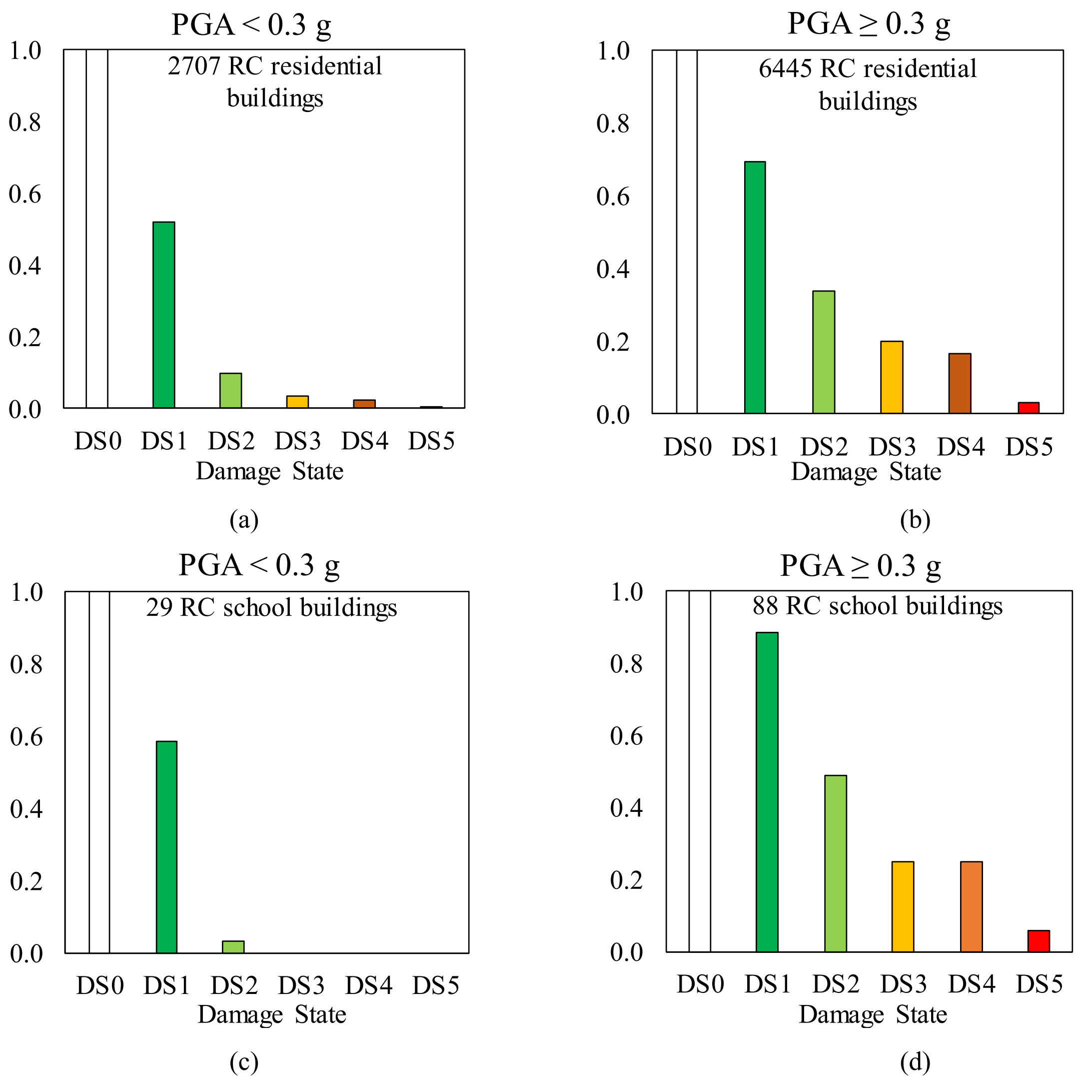

Fig. 7 – Comparison in terms of the cumulative damage state as function of the maximum PGA recorded at the site of each building: RC residential buildings (a), (b) and RC school buildings (c), (d).

The comparison outlines that residential buildings that experienced PGA < 0.3g resulted more damaged than school buildings. Indeed, an higher number of buildings classified with a DS higher thad DS2 can be found in Fig. 6a respect to the number of school buildings reported in Fig. 6b. By contrast school buildings that experienced a PGA ≥ 0.3g resulted more damaged than residential buildings.

5. Reconstruction costs

The costs of repair actions, seismic strengthening, in-situ tests for structural and geotechnical investigations, and the energy efficiency upgrading costs analysed [5,10] are summarized herein. It should be noted that such costs are related to the actual contributions made by the Italian government for repairing and strengthening the damaged buildings. The interventions and relevant costs were defined by practitioners engaged by owners according to regional price lists and considering the real earthquake damage. Component-by-component, the designer decided the repair action or to replace a component. The quotes were reviewed, amended and then approved by a technical and financial committee established by the Italian government to oversee the funding requests [5,10]. The ARCs contained in the L'Aquila reconstruction database are inclusive of: building safety measures; demolition and removal, including transportation costs and landfill disposal; repair interventions; repair and finishing works relevant to strengthening interventions; the testing of facilities; technical work for health and hygiene improvement; technical work to improve facilities; construction and safety costs; fees for the design and technical assistance of practitioners; and furniture moving. They do not include value added tax (VAT). An in depth analysis of the repair costs for RC residential buildings as function of the damaged component, drift or acceleration-sensitive components, as well as function of the achieved building and component damage state is reported in Del Vecchio et al [2].

Table 1. Mean unit reconstruction costs for RC residential and school buildings

Type of building	Usability class	No. of buildings	Repair cost*	Strength. cost	Structural and geotech. tests	Energy effic. upgrade	Total grant**
(-)	(-)	(-)	(€/m^2)	(€/m^2)	(€/m^2)	(€/m^2)	(€/m^2)
RC residential	B or C	1598	183.8	33.9	-	-	217.8
	E-B	200	342.3	139.0	4.0	39.9	525.2
	E	447	532.9	309.2	7.8	75.8	925.8
	E_{dem}	267	-	-	-	-	1213.4
RC school buildings	Retrofitted	8	427.2***		6.1	79.2	512.5
	Demolition and recostruction	13	-	-	-	-	1219.8

* The repair costs also include repair and finishing works relevant to the strengthening interventions; they do not include VAT; charges for the design and technical assistance of practitioners are included.** The total grant does not include VAT; charges for the design and technical assistance of practitioners are included; *** for school buildings the repair and strengthening cost are merged together at this stage of the analysis.

The costs of intervention for residential building change significantly with the damage level achieved by the building here represented in terms of usability class (i.e. B or C, buildigns with limited or no structural damage; E-B, buildings with a high nonstructural risk that sustained slight structural damage severe nonstructural damage; E, buildings with severe structural and nonstructural damage; Edem buildings demolished and reconstructed)

The analysis of the costs of interventions for school buildings shows that for buildings that have been retrofitted the total cost is about 512.5€/m^2. However, further analysis are need to identify the portion of this costs belonging to the repair action and the portion belonging to the strengthening. Furthermore, a detailed analysis on the level of the damage achieved by these building is needed in order to make a comparison with residential buildings.

A good match can be observed between the costs of demolished and reconstructed buildings.

6. Conclusions

This research papers reports an in depth analysis of post-earthquake data on RC residential and school buildings damaged by the 2009 L'Aquila earthquake. A large database of observational data on earthquake damage and reconstruction costs are presented and discussed with particular emphasis on the similarities and differences between these two building classes. Further research effort is need to collect data on the response of school buildings and the related costs. General conclusions cannot be drawn at this stage; however, this study provides direction for further investigations. In particular, although the school buildings significantly differs from residential ones in terms of geometry and type of non-structural component they performed similar in terms of the experienced earthquake damage. Non-structural components such as infill and partitions resulted the most damaged components often characterizing the global building damage state. In terms of the reconstruction costs, the total cost of demolition and reconstruction of the school buildings is very similar to the cost of residential RC buildings.

7. Acknowledgements

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