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ACTUAL REPAIR COSTS OF RC BUILDING COMPONENTS DAMAGED BY THE L'AQUILA EARTHQUAKE (2009)

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ABSTRACT

Recent seismic events demonstrated the high vulnerability of existing buildings and the significant damage experienced by structural and non-structural components. The recovery of earthquake stricken community passed through large reconstruction processes and involved massive economic and social resources. The building restoration process followed to the L'Aquila earthquake (2009) consisted in repair and retrofit or demolition and reconstruction of damaged buildings. This was also the occasion for monitoring and collecting the actual repair/retrofit costs of private residential buildings outside the historical center. These data were later used to calibrate the new Italian seismic risk classification of constructions rating the building seismic performance considering both structural safety and expected annual losses.
This paper illustrates the actual repair costs of reinforced concrete (RC) buildings that experienced different damage levels. An in depth analysis of the building characteristics and the observed damage to structural and non-structural components is performed. The repair cost estimates submitted and approved for funding request of 63 RC case study buildings are analyzed in detail. The repair costs, their variability and the correlation with earthquake damage is reported at component level. A focus on non-structural components (i.e. infill and partitions, acceleration or drift sensitive), is provided. Preliminary analyses outlines that the repair cost of hollow clay brick infill and partitions ranges between the 32% to 44% of the total repair cost. They represents the majority of the total repair costs and this needs to be properly considered in loss-assessment procedures or in the design of resilient retrofit solutions.

Keywords: Existing buildings; Seismic damage; Non-structural components; Infill walls; Loss-assessment;

1. INTRODUCTION

Recent seismic events outlined the importance of quantifying seismic losses and the amount of resources needed for the reconstruction. The restoration of public or residential buildings in the aftermath of the seismic event may have a significant impact on national economies. This remarks the primary role of having accurate predictions of the repair/retrofit costs in order to plan resilient strategies of intervention or have reliable loss scenario.
Nowadays reliable methodologies, such as the FEMA P-58 (ATC 58 2012), are available. Nevertheless, they commonly employ repair costs and fragility functions of components typical of the US standard (Ramirez and Miranda 2009; Whittaker and Soong 2003). This makes difficult their use for the European building stock (Del Vecchio et al. 2018).
The recent European seismic events have been a unique occasion to collect and monitor actual

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repair/retrofit costs and observational data of existing buildings (Di Ludovico et al. 2017a; b). The effort in collecting and analyzing the characteristics of residential buildings, the observed earthquake damage, the reconstruction costs and time for the building reoccupy resulted in a unique database of 5775 records (Di Ludovico et al. 2017a; b). These data can be employed as benchmark to calibrate refined or simplified loss assessment procedures, consequence functions and to validate available methodologies for the European context (De Martino et al. 2017; Del Vecchio et al. 2018). Recently, the L'Aquila database has been adopted to calibrate and validate the methodology for the calculation of the expected annual losses (EAL) at the base of the Italian guidelines for seismic risk classification of constructions (Cosenza et al. 2017).

Although great advances and relevant scientific studies were performed basing on the L'Aquila database (Del Gaudio et al. 2017; Mannella et al. 2017; Polese et al. 2018), further research effort is needed. Indeed recent seismic events highlighted that significant damage was attained in structural and non-structural components also under low-to-medium intensity earthquakes. Preliminary studies (De Martino et al. 2017; Del Vecchio et al. 2016, 2018) outlined that the repair cost to restore structural and non-structural components to the pre-earthquake condition is a relevant portion of the total reconstruction cost. Thus, a focus on the repair costs at components level for structural and non-structural members typical of the Mediterranean area is of paramount importance.

This paper illustrates the actual repair costs of reinforced concrete (RC) buildings that experienced different damage grades. An in depth analysis of the building characteristics and the damaged to structural and non-structural components is performed. The repair cost estimates submitted and approved for funding request of 63 RC case study buildings are analyzed in detail. The actual costs, their variability and the correlation with earthquake damage is reported at component level. A focus on non-structural components (i.e. infill and partitions, acceleration or drift sensitive), is provided.

2. THE L'AQUILA (2009) RECONSTRUCTION PROCESS

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 buildings. Detailed descriptions of the reconstruction policy, relevant regulations and an overview of the data related to the reconstruction of 5775 residential buildings damaged by the earthquake are reported in Di Ludovico et al. (2017a; b). The damaged buildings were classified based on the usability rating assigned in the immediate aftermath of the earthquake basing on the AeDES form (from A to F), which reflects the severity of the damage (Baggio et al. 2007). The usability rating of the 5775 buildings was: 3,546 (i.e. 62%) buildings had a usability rating of B or C (usable or partially usable building with limited or no structural damage but with severe non-structural damage) and 2,211 (i.e. 38%) buildings had an E rating (unusable buildings with severe structural and non-structural damage).

The E-rated buildings were later subject to a further classification based on more detailed seismic assessments. Two further sub-classes have been identified: E-B includes buildings with high non-structural risk and slight structural damages, where a local strengthening strategy may solve most of the structural weakness; E_{dem} includes the buildings which need to be demolished because of dangerous structural weaknesses, high residual drift, local or global collapse or economical inconvenience in the structural retrofit respect to demolition and reconstruction. It is worth noting that for E rated building the application for funding is based on a more detailed seismic assessment involving global analysis on the as-built and retrofitted configuration. More details about the building classification and the available data collected during the reconstruction process can be found in Di Ludovico et al. (2017a; b).

2.1 The costs of building restoration

The actual repair costs monitored during the reconstruction process of private residential buildings outside the historical center damaged by L'Aquila earthquake (2009) were collected, analyzed and discussed in the ReLUIS "White book" on the reconstruction process in L'Aquila (Dolce and Manfredi 2015; Di Ludovico et al. 2017a; b). Table 1 summarizes the mean actual costs normalized by

the overall building gross surface area (i.e. €/m^2) for the full set of buildings and for the subsets of RC and masonry buildings. The costs of repair actions, seismic strengthening, in-situ tests for structural and geotechnical investigations and the energy efficiency upgrading costs analyzed by Di Ludovico et al. (2017a; b) are summarized herein. Note that such costs are related to the actual contribution made by the Italian government to repair and strengthen 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 estimates (and actual repair costs) were reviewed, amended and then approved by a technical and financial committee established by the Italian government to oversee the funding requests (Di Ludovico et al. 2017a; b).
The actual repair costs included 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 works for health and hygiene improvement; technical works 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). It is worth mentioning that the reconstruction process clearly distinguished the contribution allocated for Condominium Units (termed CU), Common Areas (CA) and Independent Dwellings (ID). The funding application for CU involved the repair works only; the funding applications of CA and ID involved both repair and local or global strengthening works. Thus, in order to have an estimation of the reconstruction costs at building level for the condominium buildings it is necessary to consider both the repair costs of CU and repair and strengthening costs of CA.

Table 1. Mean unit costs related to RC and masonry buildings in L'Aquila (Di Ludovico et al. 2017a; b)

Usability rating	**Type of Structure**	**No. of buildings**	**Repair costs***	**Strength. costs**	**Structural and geotech. tests**	**Energy effic. upgrade**	**Total grant****
(-)	**(-)**	**(-)**	**(€/m^2)**	**(€/m^2)**	**(€/m^2)**	**(€/m^2)**	**(€/m^2)**
B or C	RC	1598	**183.76**	33.90	-	-	217.76
	Masonry	899	216.81	68.32	-	-	285.13
	All	2497	195.66	46.29	-	-	241.95
E-B	RC	200	**342.35**	139.01	3.99	39.90	525.25
	Masonry	44	268.29	143.70	4.27	34.30	450.56
	All	244	328.99	139.86	4.04	38.89	511.78
E	RC	447	**532.90**	309.24	7.84	75.82	925.80
	Masonry	313	447.85	320.13	10.23	59.08	837.28
	All	760	497.87	313.72	8.82	68.93	889.34

* The repair cost also includes repair and finishing works relevant to strengthening interventions; it does not include the VAT; the charges for the design and technical assistance of practitioners are included.
** The total grant does not include the VAT; charges for the design and technical assistance of practitioners are included;

The frequency distributions of these costs are reported in Di Ludovico et al. (2017a; b) along with detailed statistics.
This study focuses on the actual repair costs of RC buildings belonging to different usability classes. In particular, the repair cost about 183.76 €/m^2, 342.35 €/m^2, 532.90 €/m^2, respectively for B or C, E-B and E usability class will be analyzed in detail in order to identify the repair costs at component level.

3. COST ANALYSIS

The repair costs of a subset of buildings will be analyzed at component level. The cost estimates developed by the practitioners engaged by the owner and then approved for funding request are closely analyzed. It is worth mentioning that the cost estimates were developed according to the Abruzzo region price list (Servizio Tecnico Regionale dei LL.PP. 2011). Thus, they need to be properly converted or normalized to extent their use to the national territory. The earthquake damage to structural and non-structural components assessed by teams of expert surveyors, as reported in the AeDES form, have been also collected.

3.1 The database

This study reports the preliminary results of a subset of existing buildings extracted from the full database of 2245 RC buildings for which cost data are available. Due to the significant effort needed to collect and analyze the actual repair cost at component level, the subset is limited to 63 RC buildings, which represent about the 3% of the population. Further research effort is needed to have a significant statistical sample to derive proper statistics representative of the population. The frequency distributions of the buildings as function of the construction age, number of storeys and usability rating are reported in Figure 1a,b,c and Figure 1d,e,f for the full L'Aquila database and the subset of buildings object of this study, respectively.

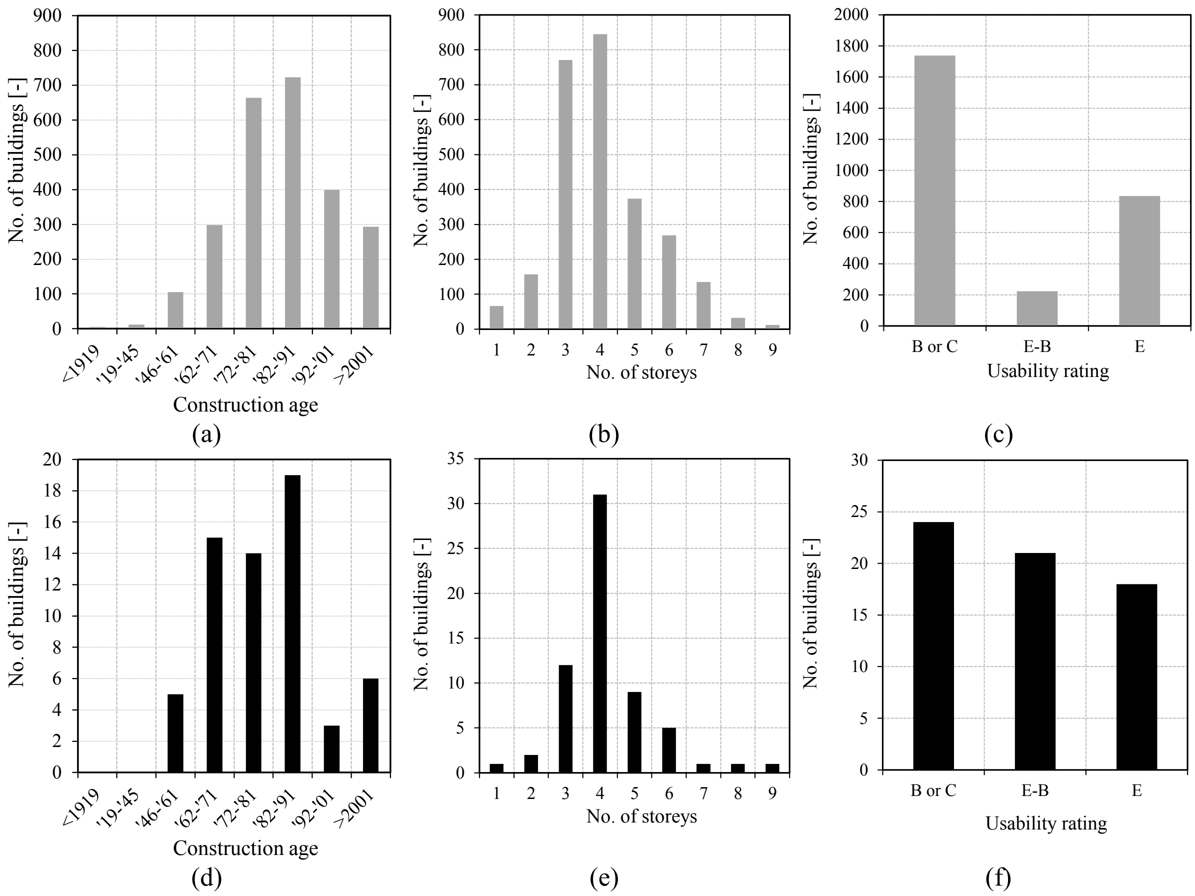


Figure 1. Frequency distribution of the building characteristics: full L'Aquila database of RC buildings (a),(b),(c); dataset of 63 RC buildings used in this study (d),(e),(f).

The frequency distributions in terms of construction age and number of storeys of the subset of 63 RC buildings (Figure 1d,e) matches with satisfactory agreement the distributions of the full database (Figure 1a,b). Higher number of E-rated buildings is needed to matches with actual distribution of the full database (Figure 1c). The frequency distributions in Figure 1d outlines that most of the buildings were built in range '62-'91 with lack of a proper seismic design. Figure 1e shows that most of the buildings of the reference subset have 3 to 5 storeys. Thus, it is worth assuming that they have several CUs that need to be considered in the analysis of repair costs along with the repair cost estimates of the CA.

3.2 Methodology for cost data analysis

The methodology proposed for the damage and cost data anlalysis for the reference case study buildings is illustrated in Figure 2.

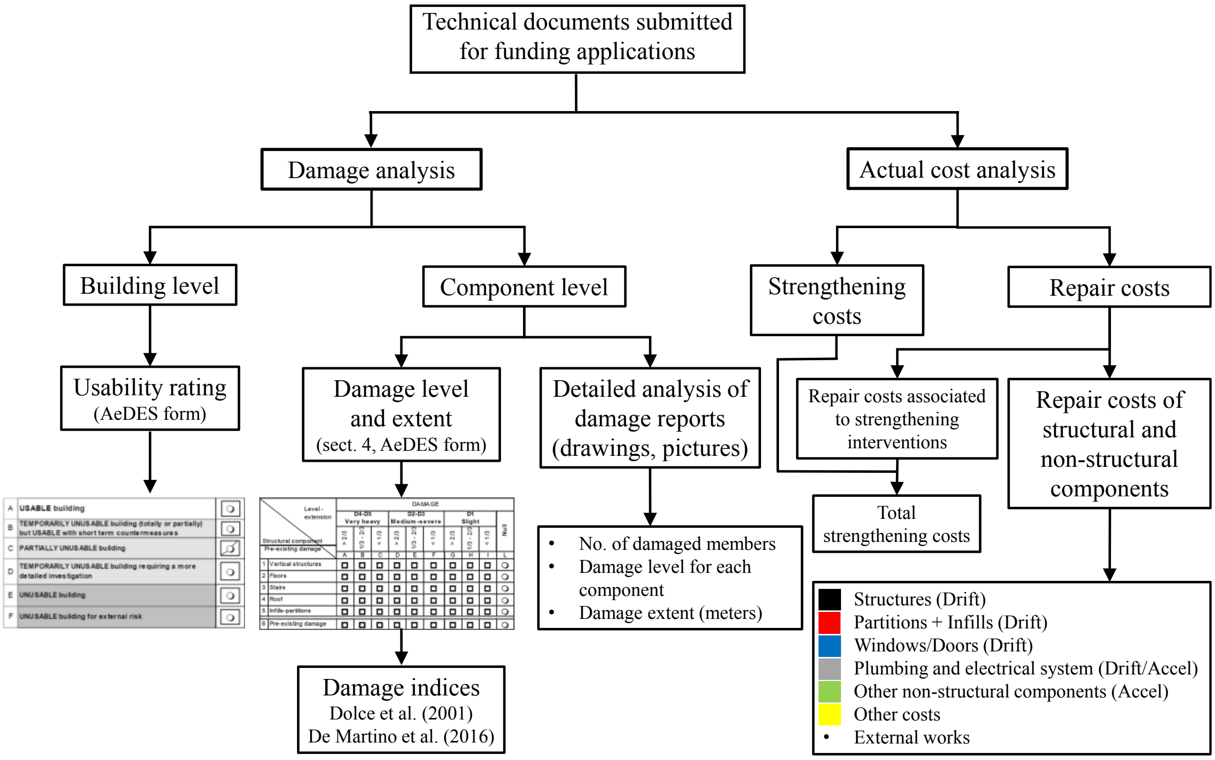


Figure 2. Methodology for damage and actual cost analysis.

The technical documents submitted for funding applications contain detailed information on the building geometry, mechanical properties, number of residential units, observed damage, technical and economic analyses on the building reparability and strengthening. In this study, the damage analysis is performed according to the AeDES form. In particular, a first damage classification at building level based on the usability rating is used (i.e. B or C, E-B, E rating). In order to have a damage classification at component level, in this study, the section 4 of the AeDES form is analyzed in detail. It classifies the earthquake damage to structural (i.e. vertical structures, floors, stairs, roof) and non-structural components (i.e. partitions and infills) based on the severity of the damage (D0 null, D1 slight damage, D2- D3 medium or heavy damage, D4-D5 very heavy damage or collapse) and its extent (<1/3, 1/3-2/3, >2/3). This damage classification allows to calculate the damage indices (Dolce et al. 2001; De Martino et al. 2017). Detailed reports including crack pattern and pictures of the damage are also included in the technical documents available for each building. These documents have been collected and will be used to have more detailed classification of the damage at component level.

The analysis of actual reconstruction costs is carried out by using the cost data available in the estimates developed by practitioners according to price list of the Abruzzo region (Servizio Tecnico Regionale dei LL.PP. 2011). In particular, both the cost estimates of CU and CA are considered. The total reconstruction costs are divided into direct cost related to strengthening interventions and repair costs. In this study, the actual *Repair cost related to strengthening interventions*, which were incorporated in the repair costs estimates during the L'Aquila reconstruction process, are quantified and summed to the direct strengthening cost. The repair cost to restore the functionality of damaged building components is the focus of this study. In order to summarize the results of the cost analysis, the repair costs are dived in six categories. The structural members are incorporated in the category *Structures*, while the non-structural components are divided in *Partitions + Infills*, *Windows/Doors*, *Plumbing and electrical system*. The category *Other non-structural components* includes the repair costs of floor finishing, roof and tiles, sanity and other equipment, communication and security. *Other costs* includes the portion of the general costs for construction field installation, safety measures, professional fees related to repair actions.

4. ACTUAL REPAIR COSTS AT COMPONENT LEVEL

In this section, the actual repair costs at component level obtained by using the aforementioned methodology are reported and discussed. The actual repair costs of each component or component groups are normalized by the overall building gross surface area (i.e. €/m^2). The mean value of subset of buildings having the same usability rating are reported. It is worth mentioning that this is a preliminary study and further analyses are needed to enrich the dataset of buildings and obtain reliable statistics.

4.1 Structural and non-structural components

The actual repair costs of building components are reported in Table 2 for subsets of buildings with different usability rating. The *Total repair cost* fully funded for the building reconstruction is reported in the last row of the table. It increases from 234.28 €/m^2 to 561.40 €/m^2 by increasing the earthquake damage at building level (from B or C to E-rating). The mean costs of the analyzed subset of buildings satisfactory match with the mean of the full database for each of the usability rating class (see Table 1). It is worth mentioning that repair costs reported in Table 2 were estimated according to the Abruzzo region price list (2009-2012). Thus, where the actual unit repair cost (€/m^2) would be used in loss assessment analyses of building located in other regions, they need to be properly converted to account for the differences in the price of materials, transportation, or labor cost. In this study, the total repair costs, which were already available in the original database for the full database of 2245 RC buildings, are divided in different categories as described above. In particular, the *repair cost for strengthening interventions* and the repair costs for *External works* are separated from the repair costs of building components (*Total building repair costs*). They are the 8% to 10% of the total repair cost.

Table 2. Mean actual repair costs of the case study buildings.

Usability rating	**B or C**		**E - B**		**E**	
No. of buildings	**24**		**21**		**18**	
Component	**Repair cost (€/m^2)**	**% Build repair cost**	**Repair cost (€/m^2)**	**% Build repair cost**	**Repair cost (€/m^2)**	**% Build repair cost**
Structures	3.07	1.42	3.07	1.00	21.54	4.75
Partitions and Infills	89.22	41.19	133.26	43.56	144.72	31.91
Plumbing and elect. syst.	27.67	12.78	40.85	13.35	63.81	14.07
*Other non-struct. comp.**	30.03	13.86	44.10	14.42	80.08	17.66
Windows/Doors	18.85	8.70	31.09	10.16	54.24	11.96
*Other costs***	47.77	22.05	53.59	17.52	89.14	19.65
Total Building repair cost*	**216.61**	**100.00**	**305.96**	**100.00**	**453.53**	**100.00**
Repair costs for strength. interv.	7.99		24.44		84.75	
External works	9.69		14.72		23.13	
Total repair cost	**234.28**		**345.12**		**561.40**	

*it includes: floor finishes, roof and chimneys, sanitary equipment, communication and security;
**it includes: general costs for construction field installation, safety measures, and professional fees related to repair actions.
*** it is the sum of the repair costs of all the building components.

The repair costs of the building components are summarized in Table 2 and Figure 3 in terms of unit cost (€/m^2) and percentage of the *Total building repair cost*. The study points out that for the case study buildings the repair costs of *structures* are significantly lower (1% to 5%) than the repair costs of non-structural components (76%-81%). In particular, the repair costs of *infills and partitions* are in the range 32% to 44% of the total building repair cost. In the Mediterranean construction system, *plumbing and electrical systems* are commonly incorporated in the hollow clay brick infills and partitions. Summing the repair costs of these components (13%-14%) to *partitions and infills* and to the repair cost of *windows and doors* (9%-12%), the repair costs of the enclosure system raise up to 58%, 63% and 67% for E, B or C and E-B rated buildings, respectively.

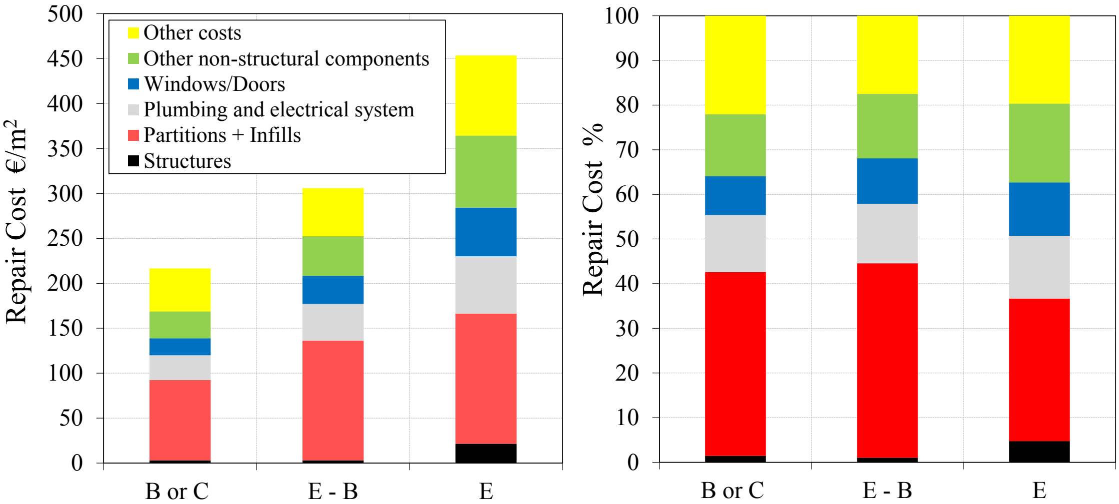


Figure 3. Mean actual repair costs of building's components.

It is worth noting that the percentage repair cost of *plumbing and electrical system*, *windows/doors* and *other non-structural components* increases with severity of the building rating. By contrast, the percentage repair costs of *infills and partitions* significantly decrease for the E-rated buildings respect to E-B and B or C. The unit repair costs of all the other components significantly increase moving from E-B to E usability class, while the unit repair cost of infills and partitions slightly increase about 11 €/m^2. Indeed, once that a significant damage has been attained in the infills and partition (opening of large cracks, which is frequent for E-B rated building) they need to be substituted leading the maximum repair cost. The latter does not significantly increase with the increasing damage.

4.2 Drift and acceleration sensitive components

In this section, the actual repair costs are grouped in acceleration or drift sensitive components. As outlined in Figure 2, *structures*, *partitions and infills*, *windows/doors* can be considered drift sensitive components, while floor finishing, roof, tiles chimney, sanitary and other equipment, communication and security (grouped in *Other non-structural components)* are acceleration sensitive.
The category of plumbing and electrical systems includes electrical cables, pipes, lighting or rain drainage systems that are both acceleration and drift sensitive. Further research effort is needed to establish the component belonging to drift or acceleration sensitive category.
The actual repair costs for drift or acceleration sensitive components are reported in Figure 4. The comparison outlines that 60% to 67% of the total building repair costs concerns drift sensitive components, while 17% to 20% acceleration sensitive. This result is of paramount importance in order to design and develop efficient retrofit solutions for existing RC buildings typical of the Mediterranean area suffering for the lack of lateral strength, stiffness and deformation capacity. It is worth noting that retrofit solutions increasing the lateral stiffness of the RC structural system with the aim to reduce the damage to drift sensitive components does not improve the seismic performance of acceleration sensitive components which could become even worst.

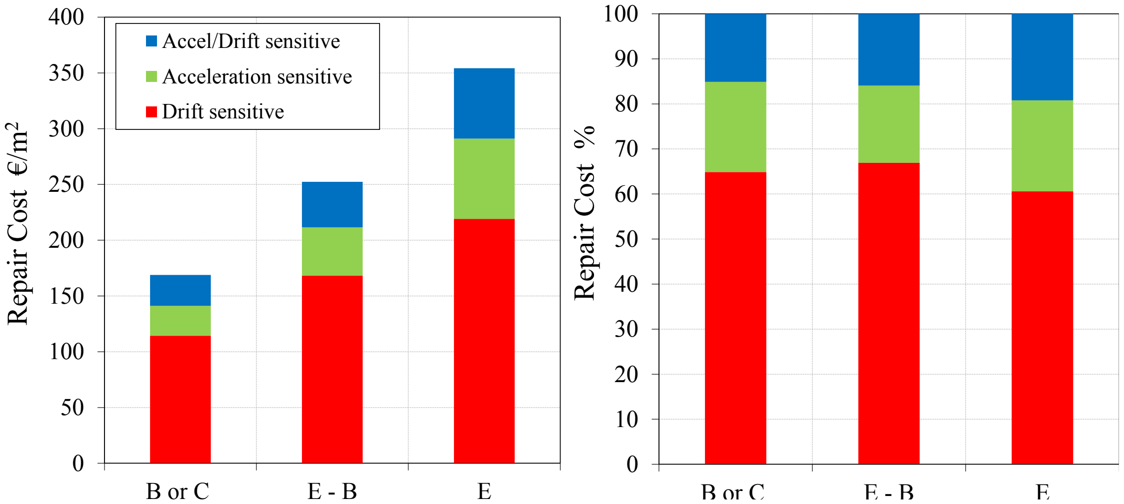
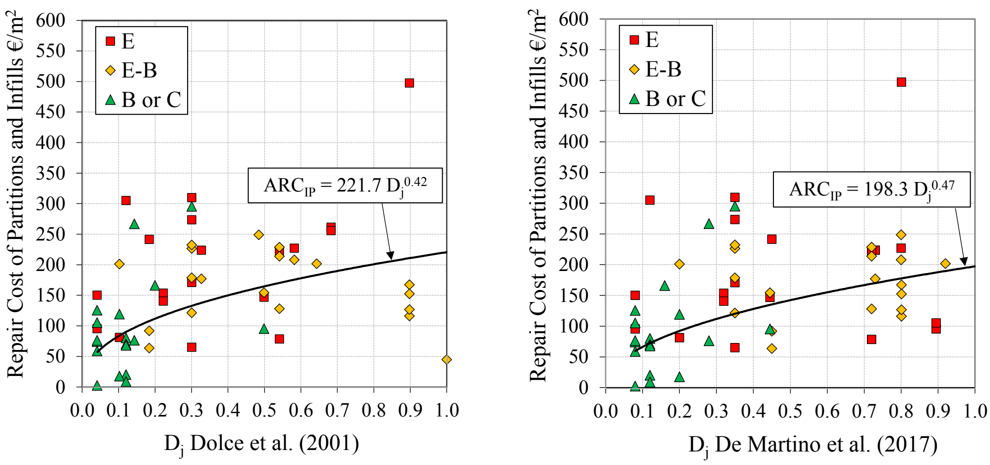


Figure 4. Mean actual repair costs of drift and acceleration sensitive components.

4.3 Correlation with damage index

This section illustrates the correlation of the repair costs of *Infills and Partitions* (summed to the repair costs of Windows/Doors) with the earthquake damage that they experienced. To this end, the damage indices of these components are computed according to Dolce et al (2001) and De Martino et al. (2017). The damage indices, D_j, are based on the damage observations on Infills and Partitions (damage level, *D*, and damage extent, *k*) available in the AeDES form, section 4 (Baggio et al. 2007). The damage index can be calculated as $D_j = \left(\sum_{D=D0}^{D5} D \cdot e_{k,D}\right)/5$ where *D* is a coefficient depending on the damage level (D0=0, D1=1, D2-D3=2.5, D4-D5=4.5) and $e_{k,D}$ is a coefficient depending on the damage extent. According to Dolce et al. (2001) $e_{k,\,D1} = e_{k,D2\text{–}D3} = e_{k,\,D4\text{–}D5} = 0.17$ for $k<1/3$, $e_{k,\,D1} = e_{k,D2\text{–}D3} = e_{k,\,D4\text{–}D5} = 0.5$ for $1/3<k<2/3$, and $e_{k,\,D1} = e_{k,D2\text{–}D3} = e_{k,\,D4\text{–}D5} = 0.83$ for $k>2/3$.
Recently De Martino et al. (2017) proposed a new calibration of the coefficient $e_{k,D}$ on the basis of the actual repair costs at building level of a dataset of 1500 RC buildings and 1000 masonry building damaged by the L'Aquila earthquake.



(a) (b)

Figure 5. Correlation of actual repair costs of Infills and Partirions (IP) with damage index (D_j): Dolce et al (2001) (a); De Martino et al. (2017) (b).

The comparison between actual repair costs and the damage indices of infills and partitions confirms that the repair costs have a significant increase at low damage indices, while a damage increase at high D_j has a low impact on the repair costs. Two different expressions have been proposed to fit the observational data. They allow to predict the ARC of Partition and Infills (including Windows/Doors) knowing the damage index, D_j, derived from the AeDES form. Further refinements are needed to reduce the variability of the repair costs. Indeed the observed damage reported in the AeDES form reflects a damage measure at level of the building and cannot accurately account for the different damage states of each infill or partition wall. Thus, a more accurate analysis of the damage level and extent (available in the design drawings and pictures) is needed to better correlate the ARC and the observed damage.

5. CONCLUSIONS

The paper presents the preliminary results of a detailed analysis of the actual repair costs of existing RC buildings damaged by the 2009 L'Aquila earthquake. A subset of 63 RC buildings is properly selected from a wide database and the actual repair costs and the earthquake damage are analyzed at component level. With reference to the subset of case study existing buildings typical of the Mediterranean area, it can be concluded that:

- The actual repair cost increases with the usability rating of the damaged building moving from B or C-rated to E-rated buildings;
- The repair cost of non-structural components represents the majority of the total building repair cost (76%-81%), while the repair cost of structures is only the (1%-5%). The remaining part is the general costs for construction field installation, safety measures, and professional fees related to repair actions (18%-22%).
- The majority of the repair cost concerns infills and partitions (32%-44%). Indeed, hollow clay brick walls as commonly found in the Mediterranean construction standards are very sensitive to earthquake loads due to their brittle behavior;
- Infills and partitions commonly incorporates the *plumbing and electrical systems.* Summing the repair costs of these components (13%-14%) to *partitions and infills* and to the repair cost of *windows and doors* (9%-12%), the repair costs raise up to 58%, 63% and 67% for E, B or C and E-B rated buildings, respectively.
- The actual repair costs of drift sensitive components is in the range 60% to 67% of the total building repair costs, while the repair cost of acceleration sensitive ones is 17% to 20%.

Finally, tentative formulations, derived from best fitting of the observational data, are proposed to predict the repair cost of Partition and Infills (including Windows/Doors) knowing the damage index, D_j, derived from the AeDES form. Further refinements are needed to reduce the variability of the repair costs, to improve the predictions and to increase the dataset of case study buildings for a detailed statistical analysis.

6. ACKNOWLEDGMENTS

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