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Repair costs of infills and partitions and correlation with earthquake damage for R.C. buildings

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ABSTRACT

Recent seismic events showed the high vulnerability of existing buildings and the relevant economic and social losses. Nowadays, the modern seismic engineering necessarily needs to account for expected economic losses in order to plan effective mitigation strategy at building and regional level. Different methodologies are available in literature and they are implemented in useful tools suitable for the application in the design practice. Recent seismic events have been a unique occasion for monitoring and collecting the actual reconstruction costs at a large scale. These data can be used to calibrate and validate the loss-assessment procedures.

This research work focuses on the actual repair costs of a database of reinforced concrete existing buildings damaged by the 2009 L'Aquila earthquake and then repaired and strengthened. The actual repair costs derived by the quotes submitted for funding applications are analyzed and a focus on the repair cost of infills and partitions (IPs), which is majority of the total repair cost, is presented. The variability of the repair costs of these components and a correlation with observed damage is investigated. High dispersions is found when correlating the repair cost of IPs to the damage state and damage extent derived from empirical data. An in-depth analysis is performed to quantify the real extent of the damage experienced by these components. This results in a significant improvement of the correlations with actual repair costs.

1 INTRODUCTION

Recent devastating earthquakes demonstrated the great impact of natural hazards on the economy of entire communities. In this context, reliable loss assessment procedures are needed to accurately estimate the expected economic losses and plan proper seismic risk mitigation strategies. Number of methodologies are currently available in literature. They can be used to predict earthquake losses at the building level (Cosenza et al. 2018; Welch, Sullivan, and Calvi 2012) or on a regional scale (Bal, Crowley, and Pinho 2008; Borzi, Crowley, and Pinho 2008; Crowley, Stafford, and Bommer 2008; Faravelli et al. 2019; Lagomarsino and Cattari 2013; Rosti and Rota 2018; Silva et al. 2014; Zucconi, Ferlito, and Sorrentino 2019). Furthermore, refined methodologies, such as FEMA P-58 (ATC 58 2012a), which is implemented in user-friendly software (ATC 58 2012b; Haselton and Baker 2018), allow for a prediction of earthquake losses at the component level. Although these procedures rely on recognized probabilistic frameworks (Cornell and Krawinkler 2000; Porter 2003), they employs theoretical repair cost functions which may neglect some of the complimentary actions needed to restore the component to its pre-earthquake condition. This may result in significant errors between predicted repair costs and the actual ones (Del Vecchio et al. 2018). Only few research works investigated the accuracy of the available procedures or repair cost functions respect to the actual data. This is mainly due to the lack of actual repair costs, which can be difficult to collect. In this context, research studies focusing on the analysis of post-earthquake observational data are of paramount important for the scientific community. The significant effort in the management of the immediate post-earthquake emergency and in the reconstruction process followed to the L'Aquila earthquake, resulted in a comprehensive database of 5,775 records, of which 2,512 concern reinforced concrete (RC) buildings (Di Ludovico et al. 2017a, 2017b). In this study, a focus on the repair costs of 120 buildings properly select to represent the full database is presented. The actual costs available in the quotes submitted by the practitioners for funding application are analysed component-by-component. Then these costs are grouped in categories of similar components and they are correlated with the empirical damage. Since the majority of the repair cost concerns the infills and partitions, a focus on these components and their correlation with the observed damage is proposed. In order to investigate on the high variability of these costs with observed earthquake damage a detailed analysis of the damage severity and damage extent showed by infills and partitions is performed. These data are then used to calibrate reliable consequence functions allowing for the accurate estimation of the economic losses related to infill and partitions.

2 THE ACTUAL REPAIR COST FOR RC BUILDING COMPONENTS

The reconstruction process following the L'Aquila earthquake (Italy, 2009) provided detailed information on building damage and actual repair/retrofit costs with respect to 5,775 residential buildings located outside the historical centers. These data have been widely investigated in recent research (Di Ludovico et al. 2017b, 2017a), with statistics reported on building populations, earthquake damage, and repair and retrofit costs at the building level. Further research effort allowed to calibrate proper loss-function at building level (De Martino et al. 2017). The damaged buildings were classified by employing the usability ratings assigned in the AeDES forms (from A to F) in the immediate aftermath of the earthquake, as such ratings reflect the severity of the damage sustained (Baggio et al. 2007). The buildings rated B or C (i.e. 62%) were usable or partially usable, with limited or no structural damage, but severe non-structural damage. The building rated E (i.e. 38%) were unusable buildings with severe structural and non-structural damage. In the reconstruction process, E-rated buildings were later subjected to a further classification based on more detailed seismic assessments. Two further sub-classes were therefore identified: E-B, which includes buildings with high non-structural risk and slight structural damage, where a local strengthening strategy may solve most of the structural weaknesses; and E_{dem}, which includes the buildings that need to be demolished. The actual reconstruction costs were grouped in macro-categories: repair costs, retrofit costs, the cost for energy retrofitting and the costs related to structural and geotechnical tests.

This study focuses on the repair costs of RC buildings. It should be noted that the 491 demolished buildings (E_{dem}) are not considered since they were analyzed separately (Di Ludovico et al. 2017b; Polese, Di Ludovico, and Prota 2018). The mean repair cost is, respectively, about 183.8 €/m^2, 342.3 €/m^2, and 532.9 €/m^2 for the B or C, E-B and E usability classes. In the following 120 buildings have been selected from the total database and the repair costs available in the quote estimated developed by the practitioners are analysed in detail.

2.1 *Database selection*

The 120 RC buildings object of this study have been randomly selected from the total database. In order to be representative of the full database, the distributions of the subset of data should match with those of the total database in terms of construction age, number of floors, usability rating. Furthermore they have been selected to match the distribution of the repair costs of the total database for each usability class. This may allow to extent the result of this study to the full database with enough accuracy. More details on the building selection and on the matching with the characteristics of the full database are reported in Del Vecchio et al. (2019).

2.2 Repair costs of component categories

The building's geometry, the damage sustained, documented by means of damage patterns and photos and detailed technical and economic analyses of building's reparability and strengthening requirements were analysed. The earthquake damage was classified at two different levels: at building level, by using the usability class and at component level by using both the section 4 of the AeDES form and the damage reports (including drawing and pictures on the crack pattern) produced by the practitioner involved in the building reconstruction.

The analyses of the actual reconstruction costs are carried out using the cost data available in the quotes developed by practitioners according to the price list of the Abruzzo region (2011). The total repair costs (TRC) are divided into direct repair costs (DRC; 1 to 7) and costs associated with strengthening interventions (8); (see Figure 4).

The DRCs for restoring the functionality of damaged building components (1 to 7) are the focus of this study. The structural and non-structural components are assembled and named according to the FEMA-P-58 classification (see Del Vecchio et al. 2018 for a detailed discussion). The repair costs strictly related to building components are grouped in the macro-category named as building repair cost (BRC). This includes the repair costs of: 1) structural components, including beams, columns, beam-column joints, slabs, stairs, roofs, foundations; 2) Infills and Partitions; 3) windows/doors; 4) plumbing and electrical systems; and 5) other non-structural components, including the repair costs of floor finishes, roofs and tiles, chimneys, sanitary and other equipment, and communication and security. In addition to the BRCs, there are also: 6) other costs, including the cost of safety measures, professional fees and construction field installations related to repair actions; 7) external works, including the repair costs related to external boxes, retaining walls, or other components external to the building; and 8) repair costs associated with strengthening interventions. Further details on the adopted methodology to collect and analyse the data are reported in Del Vecchio et al. (2019). The results showed that the majority of the cost concerns the repairing of infills and partitions (i.e., for the B or C, E-B and E building classes, respectively: 57.69, 52.48% and 42.63% of the total building repair cost, BRC). If the repair cost of plumbing and electrical system and the repair cost of windows and doors is summed to IPs, the repair costs of the enclosure system rise to 88.83%, 85.81% and 81.01% of the BRCs for E, B or C and E-B class buildings, respectively. This comprises almost the total of the BRCs, meaning that reliable loss-assessment procedures should properly account for the damage and relevant repair costs of such components.

2.3 A focus on infills and partitions

In order to have an insight on the distribution of the repair cost of infill and partitions with the earthquake damage a detailed analysis is performed in this study. As first tentative the repair cost of the entire enclosure system (i.e. IP + plumbing and electrical system + windows/doors) is plotted against the damage state obtained from the empirical data. Figure 1 shows the trend of the repair cost of IPs with the increasing severity of the earthquake damage. In this case the damage state of infill and partition (DSIP) is derived by using the data on the damage severity and damage extent available in the section 4 of the AeDES form (Baggio et al. 2007). These data are later converted in a damage state by using the conversion matrix proposed by Del Gaudio et al. (2017).

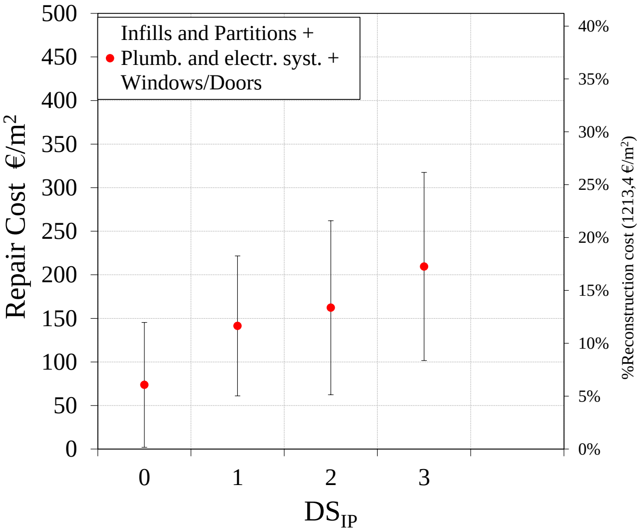


Figure 1. Actual repair cost of infill and partitions (IP)

The results outlines an increasing trend in the repair cost with the increasing DSIP. The trend is almost linear starting from a repair cost of about 75€/m^2 for a DSIP0. According to the damage classification illustrated previously, these buildings should have null damage to IPs. The significant repair cost corresponding to a null damage state could be attribute to a not accurate estimation of the damage state to IPs. Indeed a slight damage cannot be easily identified during the post-earthquake surveys. It is worth mentioning that the aim of that survey is different from a complete damage assessment, and for that reason, such damage on non-structural elements will be very difficult to be captured. A further point of discussion could be the interaction with the repairing actions of other components damaged by the earthquake. Indeed, the repairing of other structural and non-structural components may need that some repair actions should be done also to IPs (i.e. painting, replacing of wall finishing, etc.). A further in-depth analysis is needed to clarify this aspect.

Although the proposed correlation between the actual repair costs and the earthquake damage allows us to clearly identify the trends of the repair costs at the component level, high dispersion can be observed. Indeed, damage classification at the building level cannot accurately describe the DS and damage extent to each building component. As a result, more detailed analyses are required to better correlate actual repair costs and earthquake damage with the building components.

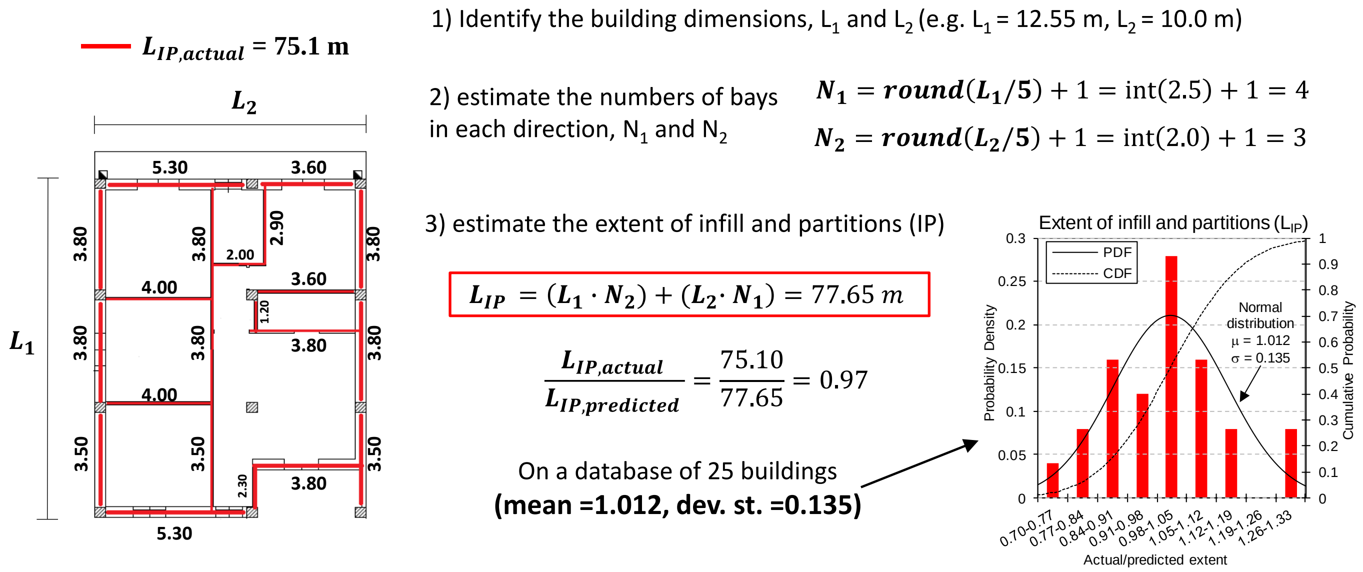


Figure 2. Procedure for the estimation of the extent of infill and partition in a RC building.

3 CORRELATION WITH MEASURED DAMAGE

In order to investigate on the actual damage severity and damage extent exhibited by infill and partitions an in-depth analysis of the reports, drawings and pictures of the damage available in the funding applications has been performed for each building.

3.1 *The extent of damage to infill and partitions*

The first step to classify the earthquake damage to IPs and the extent of the damage respect to the total quantity of these components is to have a reliable estimation of the length of IPs. To address this scope the architectural drawings available for 25 buildings have been analysed and the length of the IPs has been measured. Furthermore, data related to building in-plan dimensions, number of floors, number of bays as well as mean bay length have been collected. This allowed to calibrate a proper formulation to estimate the total length of IPs given the length of the building in the two main directions, see Figure 2. The procedure proposed to estimate the total extent of IPs is illustrate in Figure 2 2 along with a direct comparison with the measures infill length. The distribution of the ratio actual/predicted infill length demonstrated the accuracy of the proposed procedure (mean about 1.01 and standard deviation about the 0.13).

Once that the total infill length can be estimated, an in depth analysis of the damage severity and damage extent exhibited by each infill panel of the 120 RC buildings was performed. The procedure adopted to classify the damage state and measure the damage extent is reported in Figure 3.

The recognized definition of the DSs for IPs (DS - called DS_{IP} in the following) proposed by Cardone et al. (2015) and Sassun et al. (2016) is used in this study.

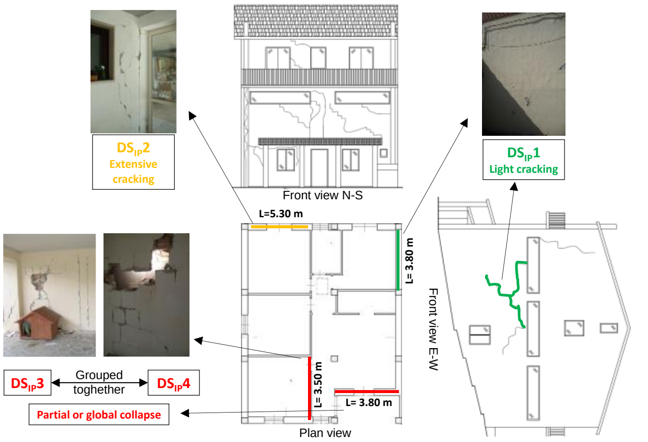


Figure 3. Damage classification and measured damage extent for infills and partitions obtained from damage reports submitted for funding applications.

Based on engineering judgements, the earthquake damage experienced by each infill or partition panel of the 120 buildings under investigation has been classified as: $DS_{IP}1$ (light cracking); $DS_{IP}2$ (extensive cracking); and $DS_{IP}3$/$DS_{IP}4$ (partial or global collapse), as also illustrated in Figure 9. In this study the $DS_{IP}3$

(partial collapse) and DS$_{IP}$4 (collapse) have been merged, as no marked differences were observed in the repair actions and relevant repair costs.

A direct analysis between the drawings, damage reports and pictures was performed to assign a specific DS$_{IP}$ to damaged IPs (see Figure 3).

Once that the actual damage extent is measured for each of the three damage states the ratio damage extent/total infill length is computed. This allow to compare the actual ratio with the damage extent reported in the section 4 of the AeDES form. In order to compare the measured damage and the estimation obtained from empirical data available in the AeDES form the damage index D_j of IPs is computed. According to Dolce et al. (2001), This factor can be computed as:

$$D_j = \frac{\sum_{D=D0}^{D5} D \cdot e_{k,D}}{4.5}$$

where: D is the coefficient corresponding to the damage level, D, (D0 = 0; D1 = 1; D2–D3 = 2.5; D4–D5 = 4.5) and $e_{k,D}$ is the coefficient corresponding to the damage extent. The latter has been taken as the actual ratio when calculating the damage index on the measured data, $D_{j,measured}$, while it is assumed equal to $e_{k,D}$ =0.17, if the damage extent is lower than 1/3, $e_{k,D}$ =0.50, when the damage extent is comprised between 1/3 and 2/3 or $e_{k,D}$ =0.83, if the damage extent is higher than 2/3. The comparison between the damage index calculated by using empirical data and the one calculated by using the measured data is reported in Figure 4.

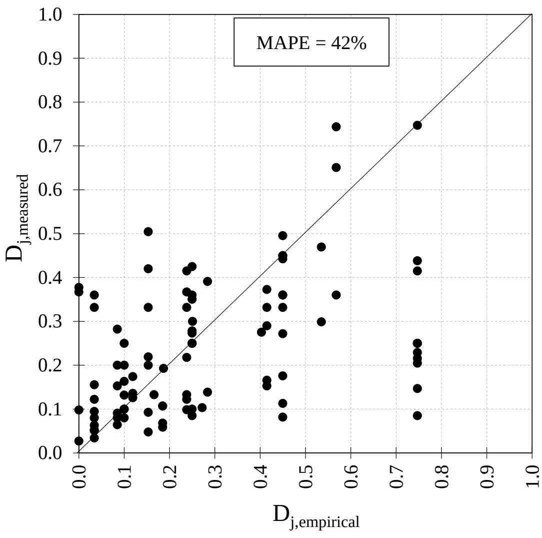
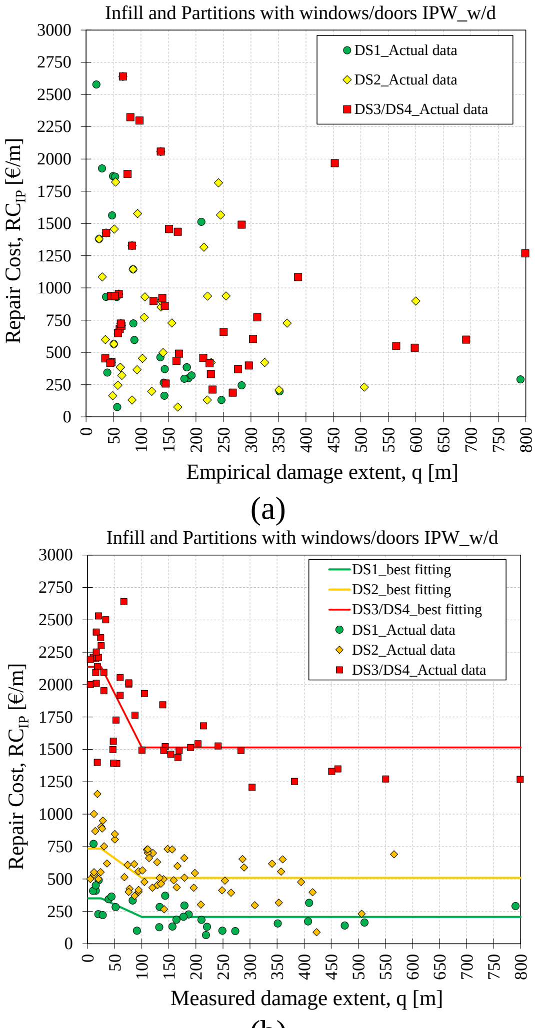


Figure 4. Empirical vs measured damage to Infill and Partitions.

The comparison outlines that an high variability is obtained when estimating the damage to infill and partitions by using empirical data. The Mean Absolute Percentage Errore (MAPE) is about the 42% which confirms that the large variability of the actual repair costs of infill and partitions is mainly related to a not accurate estimation of the damage experienced by such components.

3.2 *Repair cost vs. damage extent*

In order to investigate on the high variability of the actual repair costs of infill and partitions at different damage states they are correlated to the damage extent. Indeed, when a large quantity of the same type of work is necessary, contractor mobilization, demobilization and overhead costs can be spread over a larger volume of work, resulting in reduced unit rates. Consequence functions decreasing with the increasing damage extent are at the base of the FEMA P-58 procedure for seismic loss-assessment.



(a)

(b)

Figure 5. Repair cost of infill and partition as function of the damage extent and FEMA P-58 compliant consequence functions: empirically derived damage extent (a); measured damage extent (b).

Table 1 Calibrated consequence-function parameters for infills and partitions compliant with FEMA P-58.

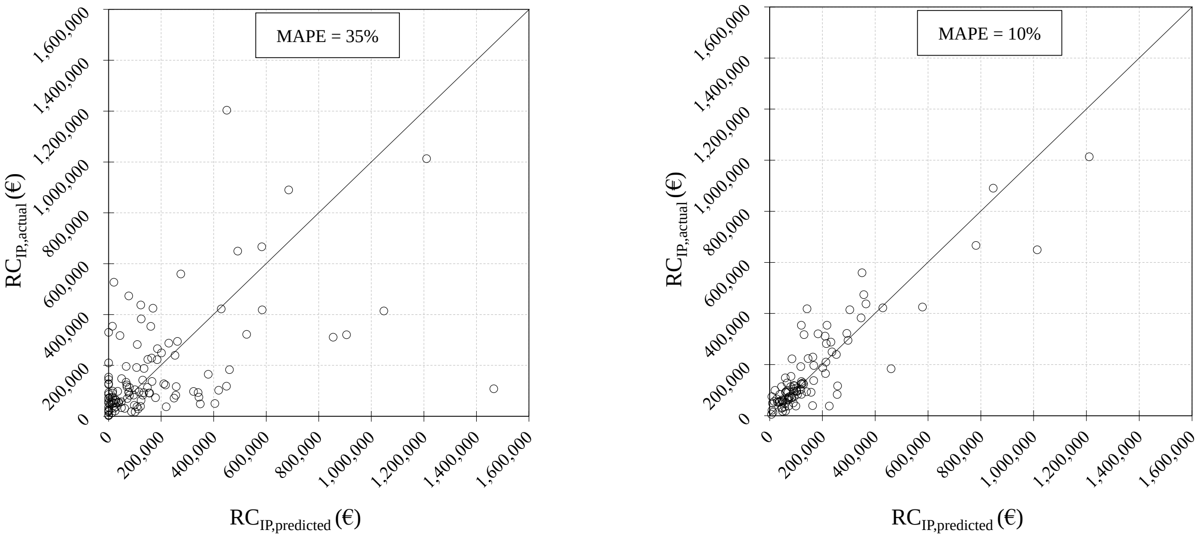
Component Type	Damage State (DS_{IP})	$RC_{IP,max}$	$RC_{IP,min}$	q_{max}	q_{min}	CoV
		€/m	€/m	m	m	-
Infills and partitions with windows/doors (IPW_w/d)	$DS_{IP}1$	350.73	207.25	100	25	0.43
	$DS_{IP}2$	734.80	508.70	100	25	0.29
	$DS_{IP}3/DS_{IP}4$	2137.23	1515.00	100	25	0.16

Note that the calibrated repair costs, RC_{IP}, do not include technical costs according to FEMA P-58 suggestions;
To convert the repair costs, RC_{IP}, from €/m to €/m^2 they should be multiplied by the height of the infill/partition wall

The damage extent, q, expressed in linear meter of damaged IPs, has been calculated as the product of the total infill length, estimated with the procedure described in Figure 2, and the damage extent obtained from the empirical data. The total repair cost obtained from quote estimates is divided for the empirical damage extent to obtain the unit repair cost in €/m. The comparison of the actual repair cost as function of the empirically calculated damage extent is reported in Figure 5a. Although a decrease of the repair costs with the increasing damage extent can be observed, a clear trend cannot be identified due to the large dispersion of the repair costs. As previously demonstrated this is due to the low accuracy in estimating the damage state and damage extent by using the empirical data.
On the other hand, Figure 5b shows that if the damage extent measured on the available drawings and damage report is used a clear trend can be observed between the repair cost and the damage extent for the different damage states.

Best fitting consequence functions, compliant with the FEMA P-58 framework for seismic loss-assessment are proposed to describe the decrease of the repair cost of IPs with the increasing damage extent. These functions, continuous lines in Figure 5b, are reported in Table 1. This study proposes reliable consequence functions calibrated on actual cost data for different DS_{IP}. These include the cost of all complementary repair actions, which are commonly difficult to predict. The shape of the function has been assumed to be in compliance with the FEMA P-58 (2012a) procedure. Trilinear functions are proposed to account for the reduction of the repair costs with increasing damage extents. These are characterized by the following parameters: lower quantity (q_{min}) - the quantity of repair actions of a given type, below which there is no discount reflecting economies of scale or operation efficiencies; maximum cost ($RC_{IP,max}$), which is the unit cost to perform a repair action; upper quantity (q_{max}), which is the quantity of repair work above which no further economies of scale or operation efficiencies are attainable; minimum cost, which is the unit cost of performing a repair action, considering all possible economies of scale and operation efficiencies; and dispersion, reflecting the uncertainty in the value of unit costs. The latter is defined by means of the coefficient of variation (CoV), which assumes that a normal distribution fits the actual repair costs well. The upper bound and lower bound limits of the damage exent q_{min} and q_{max} are set equal to 25 m and 100 m according to Cardone et al. (2015) and considering a mean length of the infill panel about 4 m.

Figure 6. Procedure for repair cost estimation of Infill and Partitions based on empirical data.



(a)

(b)

Figure 7. Repair cost estimation for infills and partitions: by using the damage extent obtained from empirical data (a); by using the actual damage extent (b)

4 REPAIR COST PREDICTION

The consequence functions developed in this study can be used to have reliable estimation of the earthquake losses for existing RC buildings in the Mediterranean area including all the supplementary and complimentary actions. In this study a first tentative to predict the actual repair costs of IPs is made by using the empirical data available in the section 4 of the AeDES form. The procedure used to predict the repair costs is illustrated in Figure 6. The economic losses can be calculated based on the rough estimation of the building dimensions in two main directions and the empirical data collected during a post-earthquake field inspection by means of the AeDES form. The damage state of IPs and the extent of the damage is obtained by using the empirical data. The damaged length of IPs can be estimated by multiplying the total infill length for the damage extent. The latter can be used as input for the available consequence functions to obtain a prediction of the repair cost associated to each damage state. The sum of the repair cost of IPs associated to the different damage state is the total repair cost. In order to assess the accuracy of the proposed procedure in predicting the repair cost if IPs the predicted cost is compared with the actual repair cost obtained from the analysis of quotes in Figure 7a. The comparison outlines that the proposed methodology may led to estimate the actual repair cost with low accuracy (MAPE about the 35%). As previously discussed, this can be attributed to an inaccurate estimation of the damage state and damage extent when obtained from the empirical data.

In order to improve the accuracy of the predictions more accurate estimations of the damage state and damage extent are needed. In this study, in order to show the reliability of the proposed consequence functions in predicting the repair costs of IPs, the actual DS and damage extent obtained from the analysis of drawings and damage reports are used to predict the repair cost.

The predictions are compared with the actual repair costs in Figure 7a. It is noting that the MAPE reduces significantly to the 10%. This confirms the reliability of the proposed consequence functions to predict the repair costs of damaged infill and partitions. It is worth noting that larger error could be obtained when the damage state and damage extent are predicted by using available loss-assessment methodologies combined with mechanically-based approach. Thus further research effort is needed to investigate this aspect. Furthermore, a calibration of a direct correlation between damage states, damage extent and the repair costs could be useful to obtain more accurate estimations by using the empirical observations.

5 CONCLUSIONS

This research study deals with the actual repair costs of a database of 120 RC buildings damaged by the L'Aquila 2009 earthquake. A focus on the repair costs of infills and partitions (IPs) which is the majority of the total repair cost and a correlation with the earthquake damage is proposed. The main findings can be summarized as follows:

- The actual repair cost of hollow clay brick IPs including the windows and doors and plumbing and electrical system, which are commonly incorporated in the walls, is about 80%-90% of the total building repair cost depending on the severity of the damage;
- A direct correlation of these costs with the earthquake damage obtained from empirical data is proposed. Although a clear increasing trend can be observed, high variability characterized the repair cost of each damage state. This is related to a not accurate estimation of the damage state and damage extent when obtained from empirical data.
- To reduce the variability of the repair cost a direct measure of the damage severity and damage extent is conducted on available drawing and damage report. This allowed to calibrate reliable consequence functions which can be used in loss assessment frameworks such as the FEMA P-58;
- The prediction of the repair cost of IPs by using damage measures obtained from empirical data could lead to significant approximations, about the 35% on average.

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