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Actual versus predicted repair costs: case studies on RC buildings damaged by L'Aquila earthquake

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Abstract

Recent seismic events confirmed the high vulnerability of existing buildings and highlighted the importance to quantify the attained losses and optimize the economic resources in the reconstruction phases. According to modern seismic design standards, damage to structural and non-structural elements are expected during the design-level seismic event. However, the building reparability and the associated costs should be evaluated in detail. This aspect is even more relevant considering that existing building may experience significant non-structural damage after medium-to-low intensity (short return period) seismic events. Thus, nowadays, the challenge of a comprehensive seismic assessment is the estimation of the earthquake-induced losses, including the "3Ds", death, dollars and downtime. Expected losses need to be considered in the retrofit design process and can be a selective criteria to identify the proper strategy and technical solution. According to these evidences, several refined or simplified approaches have been proposed in literature and they are currently under developments. Although they use rigorous methodologies, the predicted overall repair costs may require further validations. The recent seismic events represented the occasion for monitoring and collecting the direct repairing costs and real downtimes related to massive reconstruction processes (e.g. L'Aquila, 2009 and Christchurch, 2011). This paper presents a comparison of the predicted repair costs with the actual costs collected in the L'Aquila reconstruction process. The adopted methodology is described in detail and applied to case study reinforced concrete (RC) private residential buildings damaged by the L'Aquila earthquake. Refined numerical models have been developed to properly assess the seismic performances of structural and non-structural components. The predicted damage scenario well reproduce what observed during the aftermath surveys. The ATC-58 (2012) procedure, along with the recent upgrades in the fragility database, has been adopted to estimate the repair costs. The predictions are closely compared with actual repair costs grouped in meaningful categories of similar components. Similarities and differences are discussed. Further improvements to extend the adopted methodology to the Italian building stock are suggested.

Keywords: Actual repair cost, ATC-58, RC buildings, loss assessment, seismic performance.

1. Introduction

A proper quantification of expected seismic losses is nowadays of paramount importance in the performance assessment of new and existing structures in seismic prone areas. A modern seismic design of new constructions or retrofit intervention needs necessarily to account for this aspect in order to find the optimum between employed economic resources and attained losses. Only recently, the development of user-friendly automatic tools implementing the Performance Based Earthquake Engineering (PBEE) methodology made feasible the application in current practice [1, 2]. The great effort of the research community promoting and developing refined PBEE frameworks resulted in a continuous improvement and in an increasing number of applications. The Pacific Earthquake Engineering Research Center (PEER) formalized the original PBEE [3] in a more robust methodology involving four stages: hazard analysis, structural analysis, damage analysis, and loss analysis [4, 5]. The entire process has the scope to quantify the decision variables which measure the seismic performance of the facility in terms of greatest interest to stakeholders, whether in deaths, dollars, downtime, or other metrics [6]. The approach proposed by the FEMA P-58 [1] consists of a full development of the PBEE framework to make it suitable for practical applications. The performance, at a system level, in terms of risk of collapse, fatalities, repair costs, and post-earthquake loss of functionality can now be estimated and the development of a computer tool, named *Performance Assessment Calculation Tool* (PACT) [2], allows practitioners to deal with a complex framework. The attained damage states and the expected repair cost are computed using fragility and consequence functions specifically developed for the most common structural and non-structural components. The component based approach makes the proposed methodology flexible and opened to possible continuous improvements, e.g. by upgrading the fragility and consequence functions. Although it could appear that the primary scope of the FEMA P-58 project has been successfully achieved, further developments are still needed. In fact, the proposed procedure has been extensively calibrated and validated on numerical, experimental and repair/reconstruction cost estimates. As a further step forward, actual repair costs, collected in the aftermath of recent earthquakes can (and should, if available) be used to assess its accuracy and identify the criticisms in the application to different building stocks. In fact, commonly repair cost estimates tend to be low when compared with the actual office building construction costs [7]. Higher approximations are introduced when the methodology is extended to building stocks with structural and non-structural components different both in terms of materials and repair actions from U.S. standards. This can be the case of residential buildings in the Mediterranean area which commonly have stiff infill walls made of hollow clay brick which may strongly influence the structural performances and the attained losses. In fact, due to their brittle behavior, they commonly exhibited significant damage also under low-to-medium intensity earthquakes. Because they typically incorporates all the building services (e.g. plumbing, electrical system), the repair/replacement cost can be very onerous due to the amount of complimentary actions. Further major differences in non-structural components (e.g. access floor finishes, roof and chimney) may lead to significant differences in the expected economic losses. Recent research work [8] adopted the ATC-58 methodology for loss-assessment analysis on typical Italian existing frames; however the lack of data in terms of fragilities and consequence functions required the use of components typical of US construction standards. Thus, there is an urgent need to further improve and validate the abovementioned methodology for the Italian building stock. For this purpose, recently, proper fragilities and repair cost functions have been developed for hollow brick infills and partitions [9]. This paper deals with comparison of the predicted repair costs with the actual costs collected in the L'Aquila 2009 reconstruction process. Three case study buildings have been carefully selected to be representative of the full database of reconstructions costs. The predictions are closely compared with actual repair costs grouped in meaningful categories of similar components. Similarities and differences are discussed in order to provide the reader with an overview of the predicted costs and the main source of errors. In conclusion, possible directions for further improvements in the component data are outlined.

2. The L'Aquila database

The reconstruction process after L'Aquila (2009) earthquake has been a unique occasion to collect the reconstruction costs at large scale. The reconstruction process was supported by the Italian Government using public resources and the technical and financial review provided by a team of various expertise properly set up to oversee the projects and relevant funding applications. A detailed description of the reconstruction policy, the regulation and an overview of the database of 5,775 residential buildings damaged by the L'Aquila earthquake is reported in [10, 11]. The damaged buildings were classified based on the usability assessment carried out in the immediate aftermath of the earthquake. According to the AeDES form [12], the damaged building stock was organized in 6 categories named with a letter (from A to F) which directly reflects the damage severity. In order to have a more detailed overview of the actual repair costs and the influence of each class of cost on the total repair cost, three case studies have been selected from the previously described database of RC buildings. The case studies need to be representative of the entire database and with characteristics matching the mean values in terms of costs, geometry and relevant structural details. In order to reduce the uncertainty in the input motion, which may strongly affect the structural response and, in turn, the resulting damages, only buildings in the L'Aquila municipality have been considered (PGA in the range 0.3-0.6g). This study deals only with buildings rated E with the scope to quantify also the influence of structural damage (such information might be not available or not significant in buildings with usability rating B or C).

The criteria assumed for the case study selection are: total and repair costs matching the mean values of each category; age of construction and number of floors representatives of the class with highest number of buildings (generally this category has a mean total cost close to the mean value of the full database). The selected buildings are listed in Table 1. Fig. 1 shows a view of the buildings along with details of detected damages. The selected buildings are one: 3-storey building constructed in the 1982-1991 for the E-B class (B1) and one 4-storey building, 1982-1991, for the E class (B2). Furthermore, one more case study (B3) with reconstruction costs significantly higher than the mean value has been selected to identify the source of such increase in the costs. All selected buildings had a structural system with RC moment resisting frames and structural regularity in plan and elevation in order to avoid particular cases where the reconstruction costs have been affected by irregularity in the structural performances.

A summary of the selected case studies is presented in Table 1 along with the repair, retrofit, investigation tests and energy efficiency upgrade costs for the total unit, i.e. unit costs are referred to the building total surface. The seismic structural safety index pre and post (α_{ante} and α_{post}, defined as the ratio of the peak ground acceleration of the design spectrum according to the Italian current seismic code [13] and the minimum peak ground acceleration required to cause the building collapse, conventionally evaluated according to the design standard methodology) the repair and strengthening intervention and the main retrofit technique are also reported in Table 1.

Table 1 – Actual reconstruction costs for the case study buildings

								Actual costs (€/m^2)				
ID	Constr. age	Rate	Storeys	α_{ante}** (%NBS/100)	α_{post}** (%NBS/100)	Retrofit technique	Total area (m^2)	Total	Repair	Retrofit	Tests	Energy efficiency
B1	82-91	E-B	3	0.613	-	FRP	417	514.53	453.42	49.13	11.99	-
B2	82-91	E	4+1*	0.421	0.751	Base isolat.	719	839.41	396.79	352.91	9.92	79.80
B3	72-81	E	4	0.303	0.601	RC jacket	1090	1287.73	852.71	338.27	6.50	90.25

* the +1 indicates that the selected buildings has a one floor basement;

** the seismic structural safety index α is conceptually similar to the %NBS adopted in the NZSEE2006 guidelines.

The actual repair costs included in the L'Aquila 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; testing of facilities; technical works for health and hygiene improvement; technical works to improve facilities; construction and safety costs; charges for the design and technical assistance of practitioners; furniture moving. They do not include value added tax (VAT). Details on the repartition of the total reconstruction costs and the influence of different repair measures on the total repair cost are reported in Del Vecchio et al., 2016 [14].

B1 **B2** **B3**

Fig. 1 – Overview of the case study buildings.

3. Methodology

The loss assessment framework in this study follows the PEER performance-based earthquake engineering (PBEE) framework, which involves estimating dollar loss to buildings, down-time, and the number of fatalities [4]. Here, a focus on the predicted repair cost and its uncertainty based on the PEER PBEE methodology is reported. The PEER approach in the ATC-58 [1] framework for calculating dollar loss involves quantifying ground-motion hazard, estimating building response to the hazard, damage analysis and quantifying the loss associated with the response and expected damages. The four steps of the PEER framework have been addressed as follow.

- Hazard analysis: Earthquake ground shaking has been considered in the form of acceleration histories. In order to reduce the uncertainties related to the input motion only the records closer to the building sites have been considered. L'Aquila 2009 earthquake's mainshock, Magnitude (Mw) of 6.8 was characterized by a normal fault mechanism. The case-study structures were very close to the epicenter. Two accelerometric stations, whose distances is similar and less than 3 km from building sites have been selected. AQU and AQK records acquired on firm soil (i.e. B according to Eurocode 8 classification) and PGA ranging between 0.25-0.35g have been extracted from the Italian Accelerometric Archive (Itaca, [15]). Horizontal components of the chosen records were rotated in the orientation in plan of lateral resisting frames of the buildings. Geometrical formulations commonly adopted to identify the two components in near fault ground motions [16] have been adopted.

- The building performance to the specified hazard have been assessed by mean of non-linear time history (NLTH) analysis. This allows to reduce the modeling uncertainties commonly related to simplified analysis. The adopted numerical model (described below) has been extensively validated on experimental test and is able to accurately reproduce the structural and non-structural damage observed in the aftermath of the earthquake. The geometry, structural details and material properties have been specifically investigated by means of in-situ inspection and material testing. This allowed to neglect modeling and input motion uncertainties and their effects on the structural response and consequence estimates. The seismic response simulations have the scope to identify reported damage, detect potential weaknesses and potential local and global collapses and provide an estimation of the engineering demand parameters (EDP) in terms of intestorey drift and peak floor acceleration.

- Once that EDPs have been estimated, damage analysis and loss-assessment have been performed using the PACT tool [2] which implements the PEER-PBEE methodology. The intensity analysis option using two demand vectors represented by the earthquake response to the two selected ground motions has been selected for the case studies. Earthquake response in the two main building directions has been considered. Global collapse and residual drift are not considered because they were not experienced in these specific cases. Population model for multi-units residential building have been selected between the software options.
- A quantitative model for each of the building directions has been built using fragility functions available in the database and using recent upgrades to include clay brick infill walls and partitions according to Cardone et al. 2015 [9] properly implemented in the PACT. In particular, the proposed fragilities and consequence functions have been developed based on a number of experimental tests and the regional price list of repair/reconstruction actions. The repair action includes all the complimentary activities needed to restore the component to its pre-earthquake conditions. Different functions have been adopted for infills and partitions considering the presence of windows or door and services (i.e. electrical system, plumbing) commonly incorporated in non-structural walls. The other fragility functions available in the original PACT database have been adopted to complete the model. The component quantities have been estimated basing on available structural and architectural drawings and quantity surveys carried out by practitioners engaged by the owner for funding applications.

Because most of the available repair costs are provided in US dollars ($) and the actual costs are reported in the Italian currency (€) a conversion factor is needed. To convert the € in US $ and viceversa the Purchasing power parity conversion factor (PPP) [17] is used in this work. This factor is the number of units of a country's currency required to buy the same amounts of goods and services in the domestic market as U.S. dollar would buy in the United States (expressed in €/$). The mean value of the PPP factor for the year 2009-2012 (period of funding requests after L'Aquila earthquake) is about 0.77. The comparison on the cost of the most common construction materials (the cost of concrete and reinforcing steel bar have been compared using the L'Aquila, 2011 price list [18] and the costs provided by a statistical study of the California department of transportation, 2011 [19]) confirmed that the use of this coefficient can be extended to building construction costs. A specific validation on the use of this coefficient can be obtained comparing the total replacement cost of the building provided by available literature studies (about 1550$/m^2 [7]) with the median replacement cost monitored in the L'Aquila reconstruction process (1192,27 €/m^2 [11]).

4.1 Numerical models

A two dimensional refined numerical model developed in the finite element method (FEM) software Ruaumoko [20] has been adopted to assess the seismic performances of case study buildings. A lumped plasticity approach, concentrating RC member nonlinearities in critical members such as portion ends of beam and column, beam-column joints and stiff infill walls has been adopted. Number of literature studies [21, 22] and inspections in the aftermath of recent seismic events demonstrated the high vulnerability of poorly detailed beam-column joints. Numerical studies [21, 23] pointed out that modeling the nonlinear behavior of beam-column joints is of paramount importance to properly assess the building seismic performances. Same for the influence of infill walls on building global and local response. To account for these criticism in the seismic performance of existing RC frames typical of the Mediterranean area, proper capacity models and refined hysteretic rules have been proposed for beam-column joints [24], non-conforming RC members (modified Takeda, [25] and clay brick infills [26]. For this purpose the influence of joint response on rotational capacity of faming members (with not negligible effects on the interstory drift and frame deformability) has been considered including rotational springs (see Fig. 2a). Plastic hinges and lumped springs have been characterized basing on member geometries, reinforcement details and material properties available in structural drawings and material properties characterization tests performed by the practitioners engaged for funding applications. Beams and columns were modelled by mono-dimensional elastic elements with inelastic behavior concentrated at the edges in plastic hinge regions (Giberson model, Fig. 2) and defined by appropriate stiffness degrading moment-curvature hysteresis rules available in the library of Ruaumoko to account for shear strength degradation and poor transverse confinement. The modified-Takeda hysteresis model [25] was adopted for beam and column elements. The cyclic behaviour of the joint rotational spring has been modeled using the Wayne-Stewart [20] hysteresis model (Fig. 2a) able to describe the stiffness degrading characteristics of a beam-column joint with the peculiar expected pinching effects typical of cracked joints [24]. The cyclic behaviour of the infill panel was been modelled adopting the hysteresis rule proposed by Crisafulli [26] to simulate the axial response. Infill mechanical properties have been quantified according to available literature formulations [27] calibrated on experimental tests on infill wall typical of the Italian constructions. Diagonal strut connects beam and column ends in correspondence of the plastic hinges by means of stiff elements able to transmit only compression actions. This in order to account for the infill action on RC member deformability. The proposed numerical models have been widely validate at both at subassembly and frame levels [27, 28] under static and dynamic actions.

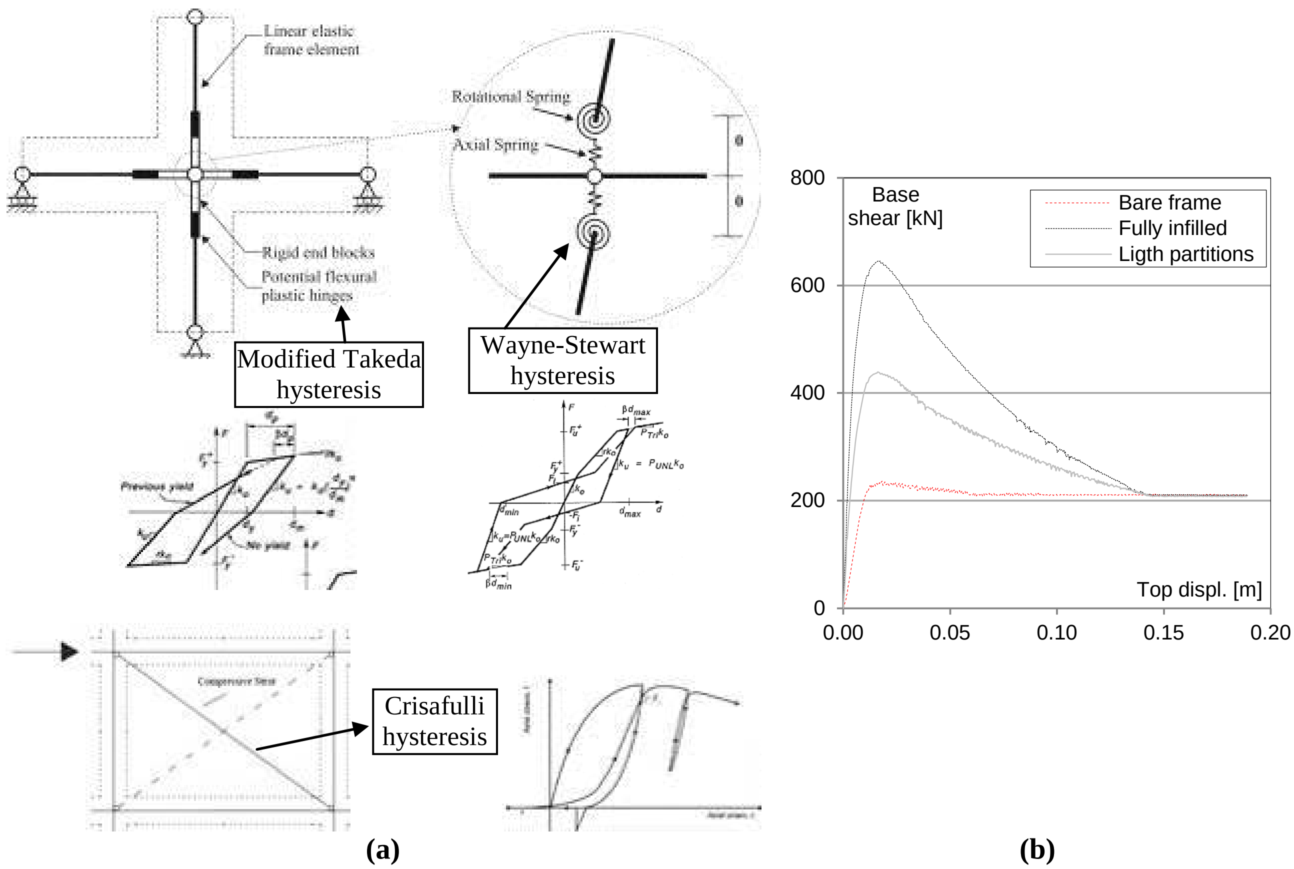


Fig. 2 – Adopted numerical model [28] and typical capacity curve of building frames.

The described numerical model have been adopted to run pushover analysis to point out the damage and collapse mechanism and the differences in terms of initial stiffness between bare, fully infilled and interior frame with partitions (see Fig. 2b). Capacity curves typical of the case study buildings show a collapse mechanism characterized by joint shear failure involving the first floor members. The infill wall and interior partition significantly affect the frame response in terms of strength, stiffness and collapse mechanism. This need to be properly accounted in the mass distribution on each frame to be representative of the overall building response.

The gravity loads assigned to the reference frame has been computed considering the frame tributary area. The numerical model of the exterior frame has been used for NLTH analysis. However, the seismic mass assigned at each floor has been computed to reproduce the overall building response in the reference direction. In particular, the mass has been distributed between bare frame, infilled frame and interior frame with light partitions as function of the frame lateral stiffness. The number of frames available in the structural system is known from structural and architectural drawings and confirmed by in-situ inspection carried by engaged practitioners for funding applications. With these assumptions the numerical model is able to reproduce with reasonable accuracy the building lateral response in each of the two directions. A further validation, comparing the predicted and observed damage is reported below.

4. Case studies

The proposed methodology has been applied to the three selected case study buildings. In order to compare the predicted and actual repair costs, EDP have been estimated using NLTH analysis. The results in terms of interstory drift and peak floor acceleration are used as input for the loss-assessment procedures using a quantity based model implemented in the PACT tool. The results are reported below.

4.1 Seismic performances

The seismic performance of the selected case study buildings have been simulated by means of NLTH analysis using two different record motions (AQK and AQU) of the L'Aquila 2009 earthquake. The records have been properly rotated in the direction of the lateral resisting frames (x and y). The floor-by-floor estimations of the two EDPs are reported in Fig. 3. The simulations pointed out that none of the buildings reached the collapse, but they experienced significant structural and non-structural damage. The largest drift are concentrated at the first floor of B1 and B3, and at the second floor for B2 with a maximum value of about 1% for B1. This confirms that existing buildings are likely to exhibit a soft-storey mechanism as a result of incorrect application (or absence in the code provisions) of capacity design principles.

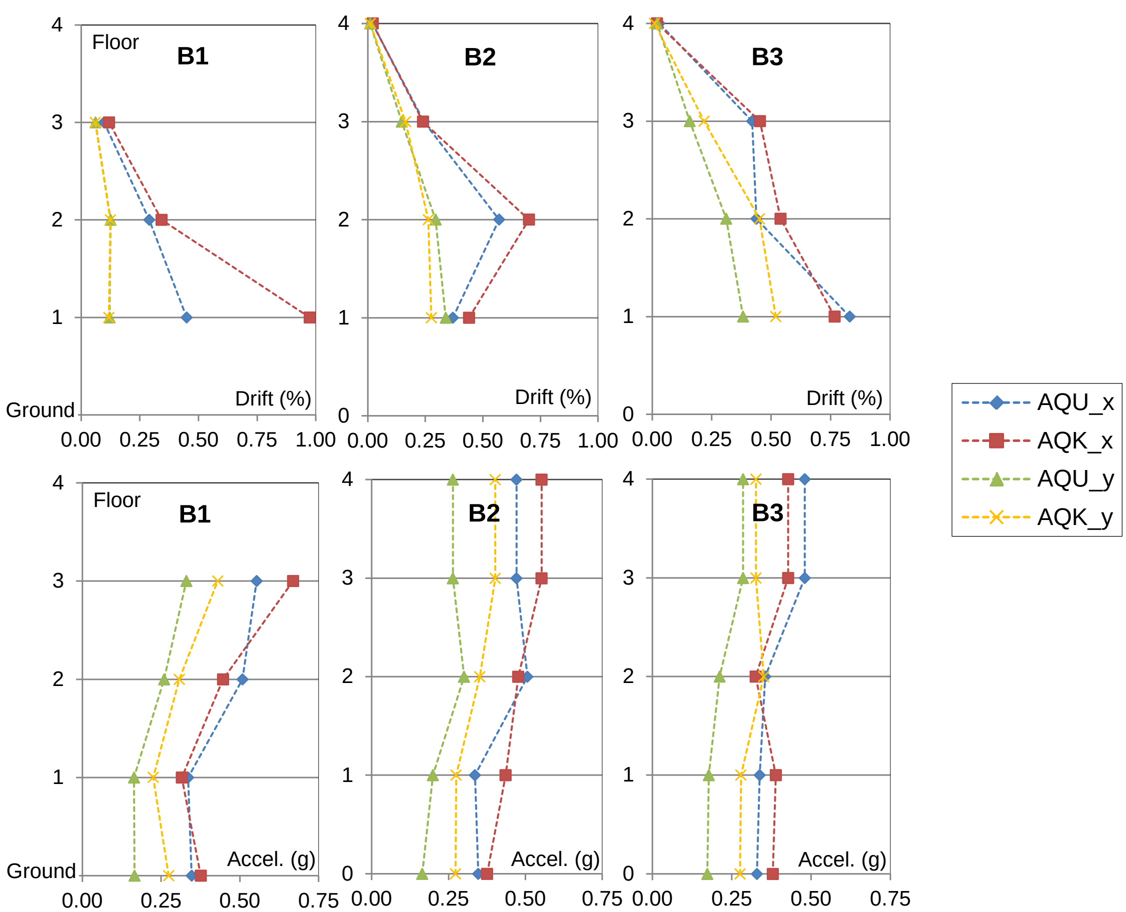
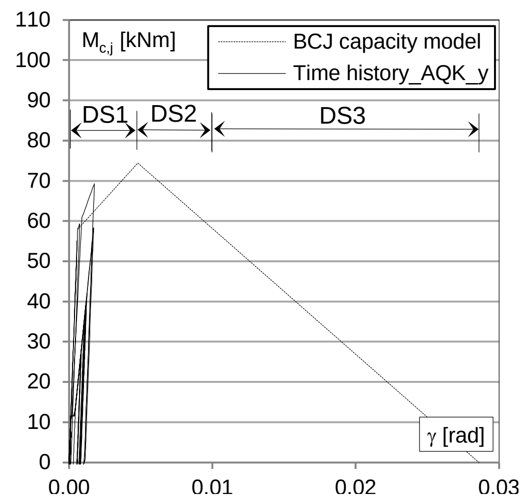


Fig. 3 – Building response resulting from NLTH analysis.

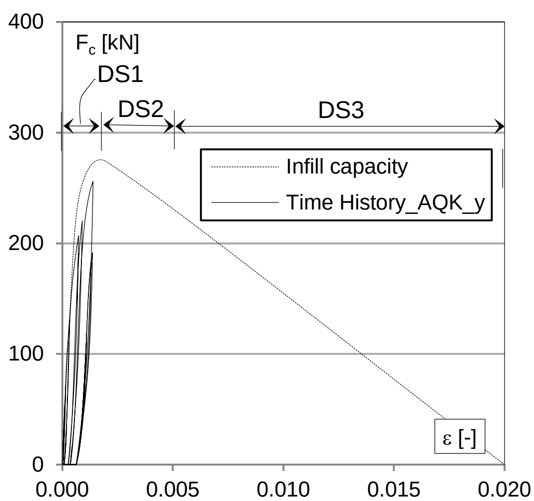
A significant amplification of the peak ground acceleration can be observed in all the case studies along building height. In particular, the maximum recorded peak floor accelerations are about 1.5-2 times the imposed PGA.

The model reliability predicting damages to structural and non-structural component can be assessed comparing the predicted and observed damages. For this purpose, damage states available in literature studies [27] for structural and non-structural components typical of Italian existing buildings have been adopted. In particular, damage to poorly detailed beam-column joints can be expressed as function of the joint shear distortion, γ: first diagonal cracking (DS1) $0.0002 \leq \gamma < 0.005$; extensive damage (DS2) $0.005 \leq \gamma < 0.01$; severe damage/incipient collapse (DS3) $0.01 \leq \gamma$. With reference to infill walls, the damages can be expressed as function of the axial strain in the diagonal compressive strut, ε'_w: no damage or minor cracking (DS1) $\varepsilon'_w < 0.002$; extensive damage (DS2) $0.002 \leq \varepsilon'_w < 0.005$; severe damage/incipient collapse (DS3) $0.005 \leq \varepsilon'_w$. The proposed models are able to capture the observed damages to structural and non-structural components. An example of the model accuracy in the damage prediction is reported in Fig. 4 for the Building 1 case study.



(a)

(b)



(c)

(d)

Fig. 4 – Comparison of predicted and observed damages on Building 2: (a) (b) First cracking and limited damage (DS1) on corner beam-column joint; (c) (d) minor to extensive cracking (DS1-DS2) on infill walls.

4.2 Repair costs

Focusing on the repair costs directly related to the seismic damage, a detailed list of the actual repair cost for each component is proposed in Table 2 along with the cost predicted with the proposed methodology and the related errors. The same component groups proposed in FEMA-P-58 approach have been used to group the components in meaningful categories. The repair cost of each category has been normalized by median replacement costs (1192.27 €/m^2) of L'Aquila RC buildings [11] as commonly found in available literature studies [7, 8, 29].

Table 2 – Actual vs. Predicted repair costs

		Repair cost/Reconstruction cost (%)								
		B1 (E/B)			B2 (E)			B3 (E)		
		Actual	PACT	Δ (Δ%)	Actual	PACT	Δ (Δ%)	Actual	PACT	Δ (Δ%)
Drift sensitive	Partitions*	12.0	4.8	7.2 (60%)	6.1	4.7	1.4 (23%)	16.1	5.6	10.6 (66%)
	Infills*	11.8	9.4	2.4 (20%)	7.7	4.5	3.2 (42%)	11.1	7.2	3.9 (35%)
	Beam-column joint (BCJ)	-	-	-	0.3	0	0.3 (100%)	1.5	8.7	-7.2 (-494%)
	Stair finishes	0.3	0	0.3 (100%)	0.1	0	0.1 (100%)	0.5	0	0.5 (100%)
Accel. sensitive	Access Floor	8.9	0.5	8.4 (95%)	2.1	0.3	1.8 (87%)	3.2	0.3	2.9 (90%)
	Roof and chimney	0.3	6.0	-5.7 (-2000%)	2.2	2.9	-0.8 (-34%)	1.3	0.6	0.8 (56%)
	Lighting	0.5	1.8	-1.2 (-230%)	0.3	0.6	-0.4 (-144%)	0.0	0.5	-0.5 (-100%)
	Sanitary equipment**	0.7	0	0.7 (100%)	0.4	0	0.4 (100%)	-	-	-
	Rain drainage system**	0.2	0	0.2 (100%)	0.9	0	0.9 (100%)	-	-	-
	Comm. & security**	0.6	0	0.6 (100%)	0.1	0	0.1 (100%)	-	-	-
Total building repair cost		35.2	22.4	12.8 (36%)	20.3	13.1	7.2 (35%)	33.7	22.8	10.9 (32%)
	External works	1.6	-	-	2.1	-	-	18.3	-	-
	Other costs***	0.6	-	-	10.9	-	-	19.7	-	-
	Total repair cost	37.4	-	-	33.3	-	-	71.7	-	-

* The costs include restoring infill/partition finishing, windows, doors, plumbing and electrical system;

** The fragilities and repair costs of these elements are currently not available;

*** Includes the general costs shared with other categories.

The actual and predicted repair costs of each component presented here include all the repair actions needed to restore the final product to the pre-earthquake conditions. It is worth noting that total building repair costs do not match the data reported in Table 1 because they have been discounted for the portion of the costs shared with the other categories (e.g. the fixed costs of building safety measures, the installation of construction site, named Other costs) and for the repair cost of components external to the building. Furthermore, as proposed in the FEMA P-58 approach, they do not include the costs of design consultants, technical assistance and building administrator cost. Based on the data acquired during the L'Aquila reconstruction process [10, 11], they represent a relevant cost in the building reconstruction process and need to be properly estimated.

The actual repair costs for the selected case study building range between 33% and 72% of the total replacement costs. However, only a portion about the 20 % to 35% of the total replacement costs can be attributed to repair actions on the building. The rest of the cost included in the repair measures is due to external works or other costs. The latter have not been considered in this study because the ATC-58 methodology only refers to repair costs of the building.

A focus on the building repair costs is depicted in Fig. 5. The ATC-58 methodology applied as described before, including recent upgrades on the fragility and consequence functions for hollow clay brick infill and partition, allows to estimate the repair costs with errors about the 7 % to 13% of the total replacement cost. Thus, significant differences still exist in the estimation of actual repair costs. Analyzing the proposed categories, it can be observed that drift sensitive nonstructural components (i.e. infill and partitions) constitutes the majority of repair costs. Here there is also the largest gap, 2% to 10% of the total replacement cost, with predicted costs.

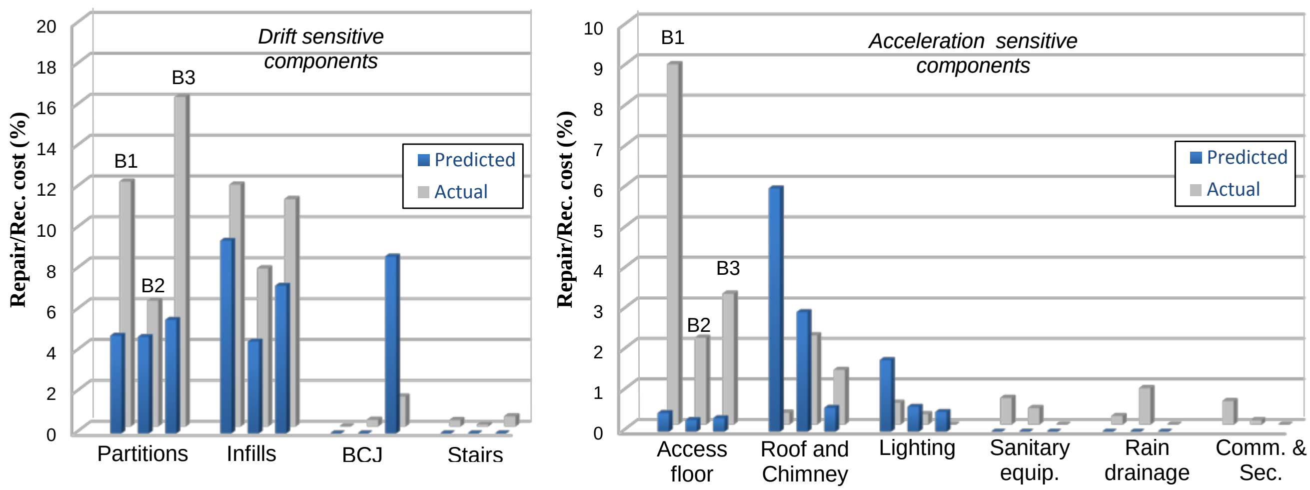


Fig. 5 – Comparison between actual and predicted repair costs: (a) drift sensitive components; (b) acceleration sensitive components.

Other significant differences can be observed in the repair costs of structural components grouped in beam-column subassemblies (BCJ). In fact, the fragility functions available in the PACT database refers to structural members typical of US standards. This resulted in large gap in the estimation of repair costs. In particular, minor repair actions consisting in minor crack filling are not contemplated in the available repair actions. On the other side, the predicted repair costs are significantly higher once that significant structural damages are attained.

With reference to acceleration sensitive nonstructural components, the predicted repair cost of access floor (assumed as a percentage of the total replacement cost) are significantly underestimated. This can be due to the different construction practice and the more sophisticated materials adopted in the Italian residential buildings.

Number of fragilities, as well as they have been considered in the PACT component taxonomy, are still lacking. This is the case of sanitary equipment, rain drainage systems and communication and security.

5. Conclusions

The paper illustrates a detailed methodology properly developed to compare actual repair costs of case study private residential buildings damaged and repaired after L'Aquila, 2011 earthquake (Italy) with repair costs predicted using the ATC-58 methodology. Three case study buildings have been selected to be representative of a wider database of RC buildings repaired and strengthened in the aftermath of the L'Aquila earthquake. The repair costs, extracted from quantity surveys submitted for funding applications, have been collected in meaningful categories typical of the Italian building stock and comparable with available components in the ATC-58 database. A refined numerical model, validated on number of experimental tests, has been adopted to assess the building response by means of NLTH analysis. The proposed models are able to capture the damage to structural and non-structural components observed in the aftermath of the earthquake. The engineering demand parameters in the form of interstory drift and peak floor acceleration have been used as inputs for the PACT tool implementing the ATC-58 loss-assessment approach. The recent upgrades in the fragility database to include non-structural components typical of Italian building stock have been used in the study. Repair costs, normalized by the building replacement costs, have been computed and compared at component level. The main findings can be summarized as following:

- the total building repair costs for the selected case study ranges between 20-35% of the building replacement cost. The majority of the cost concerns non-structural components. Infills and partitions (which include plumbing and electrical system, as commonly found in the Italian construction practice) reported the highest repair costs. Acceleration sensitive components such as access floor, roof and chimney are also relevant;

- total predicted repair costs are significantly lower than actual costs, in the range 7-13% of the total replacement cost;

- the main sources of error (until the 10% of the replacement cost) concerns the repair cost of infill and partitions. Even though the adopted fragility and consequence functions have been properly calibrated for hollow brick walls, refinements are needed to improve the estimations including the cost of all the activities commonly associated to the building repair intervention;

- fragility and consequence functions for RC structural members (in the form of beam-column joint subassemblies) need to be developed for poorly detailed RC members typical of existing buildings in the Mediterranean area. As well as they do not significantly affect the total repair cost, a relevant overestimation can be observed for Building 3.

- with reference to the acceleration sensitive non-structural components, the predicted repair cost of access floor (assumed as a percentage of the total replacement cost) are significantly underestimated. This can be due to the different construction practice and the more sophisticated materials adopted in the Italian residential buildings.

6. Acknowledgments

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