ORIGINAL RESEARCH

A component-level methodology to evaluate the seismic repair costs of infills and services for Italian RC buildings

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Abstract

The reliable estimation of seismic losses due to damage to buildings is paramount for the post-emergency management and the planning of recovery activities. For residential rein-forced concrete (RC) infilled buildings, a significant role in the computation of seismic loss is played by non-structural components, above all infills, partitions and services, as shown in past earthquakes. In this work, a component-based methodology is proposed to assess seismic losses for residential RC buildings in Mediterranean region. The attention is focused on the repairing activities for masonry infills (typical enclosure or partitions elements in Italian and Mediterranean RC buildings), and for services (plumbing systems, electric equipment, floor/wall tiles…), commonly enclosed within the infill panels for the considered building typology. The described methodology can be used starting from the expected damage level to infills and partitions. It adopts given repair unit costs at differ-ent damage states of infills. The loss estimation methodology has been, first, validated by comparing predicted and actual repair costs for specific case-study buildings damaged by L'Aquila (Italy) 2009 earthquake. Then, the methodology has been applied to a wide data-set of RC buildings (about 2500 residential buildings) damaged by L'Aquila earthquake available from the literature, to show its possible application at a large-scale level. A good agreement between observed and predicted costs is obtained both for specific case-study buildings and for the wider building stock, especially when damage to structural compo-nents is very limited.

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1 Introduction

The high seismicity, combined with the significant exposure, makes Italy one of the countries where the consequences of earthquakes are more devastating than elsewhere. Dolce et al. (2019a) estimate that the earthquakes with magnitude between 5.5 and 6.9, occurred in Italy from 1976 to 2012, caused monetary losses for over €150 billion, due to recovery and reconstruction costs. In addition, Italian buildings inventory is characterized by strong deficiencies, being generally constructed before the enacting of seismic codes. Similar issues should be face up in many other seismic prone areas in the Mediterranean region and worldwide.

Seismic vulnerability represents the only factor that can be reasonably used to mitigate the effects of earthquakes though planning strategies of intervention for risk reduction at regional/national scale. To this end, the estimation of repair costs after seismic events can be paramount in defining the feasibility and/or the convenience of public incentives plans for seismic risk mitigation (Cosenza et al. 2018). Additionally, costs associated with natural hazards that can occur during the service lifetime should be properly considered in life-cycle cost assessment, in the design and management of infrastructures or buildings portfolio (Chang and Shinozuka 1996; Kang and Wen 2000; Jalayer et al. 2011; Li et al. 2020).

Different methods for loss assessment have been developed in the last fourty years in the literature. Some of them assess losses starting from damage at "building level", by using empirical Damage Probability Matrix (DPM) or empirical/analytical fragility curves (Rossetto and Elnashai 2003; Gautam et al. 2018; Del Gaudio et al. 2017, 2019a; Rosti et al. 2019b, among many others). Other approaches estimate losses at component level, starting from (quite recent) studies from the literature that have addressed the definition of DPM or fragility curves at a (structural- or nonstructural-) component level (e.g., Aslani and Miranda 2005; Pagni and Lowes 2006; ATC 58 2012a, b; Del Gaudio et al. 2019b, among others), sometimes empirically relating the intensity measure due to a seismic scenario to the damage suffered by specific building components (Del Gaudio et al. 2017; Adhikari and Gautam 2019).

The first loss estimation approaches from the literature (Guagenti et al. 1988; Yang et al. 1989; Colonna et al. 1994; Bramerini et al. 1995; Di Pasquale and Orsini 1998) evaluate expected annual losses from the probabilistic convolution of hazard and vulnerability. Differences among the mentioned evaluations regarded: (1) the way of assessing seismic hazard; and (2) the way of characterizing vulnerability, by means of DPMs and damage factor (DF) (equal to the ratio between repair cost and the complete replacement cost, for different damage levels at building level). Later, Di Pasquale et al. (2005) provided a refinement and extension of the previous methods. They developed a "probabilistic" method that returns the complete risk probability curves for four buildings typologies and for the whole dwellings population in Italy considering all the events occurring in a time period.

In Crowley et al. (2008) and Bal et al. (2008) seismic loss assessment was performed by means of the DBELA method (Crowley et al. 2004) to characterize the vulnerability. In Crowley et al. (2008), the mean damage ratio related to reinforced concrete (RC) buildings of 150 municipalities of Marmara Region is evaluated using the Boore (1997) ground-motion prediction equation related to a given scenario earthquake and DF based on HAZUS (FEMA 2003) suggestions. In Bal et al. (2008), social losses (injuries and deaths) are evaluated for a huge building stock located in the northern Marmara region

(made up of both RC and masonry structures) for a scenario involving the rupture of the Main Marmara Fault close to Istanbul in a Mw 7.5 earthquake through the use of the model proposed by Spence (2007).

Recently, Silva et al. (2018), Dolce et al. (2019b) and Rosti et al. (2019a) developed seismic risk maps for Italy reporting the average annual loss due to ground shaking through the use of fragility curves for building "classes". In Silva et al. (2018), fragility curves developed by Borzi et al. (2008) and Ahmad et al. (2010) were used. In Dolce et al. (2019b), fragility curves derived by a delegation of the scientific engineering community (Eucentre—European Centre for Training and Research in Earthquake Engineering—and ReLUIS—Laboratories University Network of seismic engineering) were adopted. In Rosti et al. (2019a), fragility curves empirically derived for residential masonry (Rosti et al. 2019b) and RC buildings (Del Gaudio et al. 2019a) were applied.

On the other hand, a new generation of methods developed in the context of FEMA P-58 (ATC 58 2012a, b) approach. They proposed the estimation of seismic losses as the sum of the contribution of each involved component, thus, requiring the use of fragility functions and consequence data for each component separately. In FEMA P-58, the Performance Assessment Calculation Tool (PACT) was introduced, integrating the results of structural analysis with a wide repository of fragility and consequence functions for a broad selection of components. In O'Reilly and Sullivan (2018) and Del Vecchio et al. (2018), PACT procedure was adapted to the Italian building stock. In both cases, an upgrade of fragility database for components typical of the Mediterranean area, such as masonry infills, is carried out. In O'Reilly and Sullivan (2018), loss assessment of Italian RC frame buildings with masonry infills was pursued. In Del Vecchio et al. (2018), predicted repair costs evaluated for five case study RC buildings damaged after L'Aquila (2009) Earthquake found good agreement with actual costs, available from funding requests, both at building level and at component level (infills and partitions, structural subassemblies, floor finishes, and other acceleration sensitive, non-structural components).

Moreover, some methods provided a compromise between the rigour of a component-based approach and the simplicity of an approach based on global damage at the building level, introducing some simplifications in the loss estimation procedure. In Ramirez (2009), the introduction of relationships between structural response and repair cost for each story allows the simplification of the PEER's framework (Aslani and Miranda 2005). As a matter of fact, Ramirez (2009) derived pre-elaborating specific fragility functions for components of each storey and the corresponding repair costs. These relationships were also used in Welch et al. (2014) within a loss assessment procedure using the Direct Displacement-Based Assessment procedure, adapted from Sullivan and Calvi (2011), incorporating also uncertainties in seismic capacity and demand. Furthermore, a simplified approach was developed in Perrone et al. (2019) to evaluate the Expected Annual Loss (EAL) of RC buildings using the results of structural analyses and a closed-form expression, arising from the assumptions of: (1) linearity between the repair costs and seismic intensity, and (2) of linear approximation of the hazard curve in log–log space.

Lately, several methods (De Martino et al. 2017; Del Vecchio et al. 2019) have developed to empirically relate repair cost information from funding requests and damage to buildings subjected to post-earthquake inspections after recent events occurred in Italy. In De Martino et al. (2017), a database of 1500 RC and 1000 masonry buildings damaged after the 2009 L'Aquila earthquake have been deeply analysed. The Authors provided the actual repair costs for the investigated real buildings (obtained by the actual projects performed by practitioners involved in the reconstruction process in the aftermath of the seismic event), depending on their post-earthquake usability judgment.

Based on such data, they also proposed an empirical correlation between the actual building repair costs and their post-earthquake observed damage. In Del Vecchio et al. (2019) a smaller dataset (120) of RC buildings has been used to analyse in detail the correlation between actual repair costs and observed damage both at building level and at component level, emphasizing the strong contribution given by hollow clay brick infills and partitions in the overall repair cost estimation.

Even though infills and services generally represented the most significant portion of economic losses due to earthquakes (Dolce and Goretti 2015; Del Gaudio et al. 2016; Del Vecchio et al. 2019), especially in the Mediterranean area, they have been specifically considered in loss estimation approaches in the literature only very recently. As a result, a careful estimation of all the required repairing activities for infills/partitions and related services is still necessary and crucial to predict the expected seismic losses for RC buildings in a reliable way.

1.1 Research significance

Several studies in the literature analysed damage to buildings or infrastructures due to the last seismic events (1981 Irpinia (Italy), 1994 Northridge (USA), 2009 L'Aquila (Italy), 2011 Lorca (Spain), 2015 Gorka (Nepal), 2016 Centre Italy). More in detail, about RC buildings, typical detected "deficiencies" are represented by: lack of sufficient reinforcement in columns, presence of squat columns leading to brittle failure, lack of confinement in columns, insufficient overlap of reinforcement, strong beam/weak column hierarchy, beam-to-column joint failure (e.g., Ricci et al. 2011; Gautam and Chaulagain 2016; Ruiz-Pinilla et al. 2016, among many others). The presence of infills, particularly in residential RC buildings, can further emphasize some of these structural deficiencies, and often being responsible for significant damage (Stratta and National Research Council 1981; Ricci et al. 2011; De Luca et al. 2014; Gautam and Chaulagain 2016; Del Gaudio et al. 2017; Furtado and De Risi 2020) and resultant direct losses (De Risi et al. 2019).

Despite the very significant number of studies that highlight existing structural or nonstructural deficiencies and resulting damage due to historical earthquakes, in very few cases researchers were able to explicitly quantify the loss contribution of each damage component to the total losses due to a seismic event. This is particularly true for nonstructural components like infills and services (Taghavi and Miranda 2003; De Risi et al. 2019; Del Vecchio et al. 2019). L'Aquila earthquake represented a unique opportunity of analysis of actual data, since, in the aftermath of the event, official statistical data about actual repair costs have been collected by analysing the technical and financial information that technicians submitted to the government for approval procedure for funding aids (Dolce and Manfredi 2015; De Martino et al. 2017; Di Ludovico et al. 2017a, b). Some of these studies started highlighting that the percentage influence of infills and services on the total repair cost was significant, and, thus, worthy to be investigated and duly considered, as addressed in the present work.

In this research work, a component-based methodology to assess seismic losses for typical Italian and Mediterranean residential RC buildings is proposed. A specific focus for such estimation is addressed to:

- masonry infills, typical enclosure or partitions elements in RC buildings, and
- services, like plumbing systems or electric equipment.

For the investigated buildings typology, services are generally allocated within the infill panels (such as electric equipment or heating hot water piping), thus making the refurbishment of the former strictly related to damage suffered by the latter. This assumption allows avoiding the use of component fragility functions specifically derived for services, and simply using fragility functions for infill panels to determine damage to both infills and services. Obviously, this simplification makes the loss estimation procedure proposed herein particularly suitable for RC buildings with bricks masonry infills where this hypothesis is fulfilled, which overall represent the great majority of the residential RC buildings in the Mediterranean area. On the contrary, different approaches should be used if services are allocated elsewhere, for example within suspended ceilings, requiring the use of specific fragility functions.

The loss estimation methodology described herein allows predicting repair costs starting from the expected damage level to infills and partitions, both predicted by means of numerical tools or directly obtained by post-earthquake in situ surveys. Repair costs are determined through a detailed list of repairing activities, unit costs, and area of intervention for different damage states (DSs), coherently with the EMS-98 (Grunthal 1998) macro-seismic scale.

The proposed methodology is validated, first, by means of the comparison with actual repair costs related to some case-study buildings damaged after L'Aquila (Italy) 2009 earthquake, based on post-earthquake observed damage. Then, the same procedure is applied to a wide dataset of RC buildings (about 2500), coming from the same post-earthquake dataset. The good agreement between actual and predicted repair costs, both for specific case-study buildings and for a wider building dataset, provides a promising validation of the proposed loss estimation procedure and its potential for large scale applications.

2 Damage states definition for infills and partitions

In the past, several researchers analysed how define DSs of RC buildings (e.g., Grunthal 1998; Baggio et al. 2007), and qualitative and quantitative described the severity and the extent of cracking patterns involving structural and non-structural components for each DS. Some of them dealt with the definition of DSs specifically for non-structural elements, as infills and partitions (Cardone and Perrone 2015; Sassun et al. 2016; Del Gaudio et al. 2019b), the main focus of this research work. In this section, DSs definitions according to Grunthal (1998) and Baggio et al. (2007) are reported and compared, since they will be later adopted in the following sections and since they represent the main reference for the more recent studies about this topic (Cardone and Perrone 2015; Sassun et al. 2016; Del Gaudio et al. 2019b).

First, EMS-98 (Grunthal 1998) defined five DSs for earthquake-damaged buildings. For RC buildings, three of them were specifically dedicated to damage to infills and partitions, as shown in Table 1; the last two DSs were related to damage to RC elements only, in the hypothesis that, beyond DS3, infills have already collapsed. DS1, DS2, and DS3 according to EMS-98 (Grunthal 1998) basically differ to each other depending on the severity and the extent of cracks in partitions and infills, from "slight" to "heavy" damage, as reported in Table 1.

Table 1 Relationship between DSs defined by Grunthal (1998) and Baggio et al. (2007)

EMS-98 (Grunthal 1998)		Baggio et al. (2007)	
DS0	No damage	D0—Null damage	DE
DS1	Negligible-slight damage: Fine cracks in partitions and infills	D1: slight damage	< 1/3
			1/3–2/3
			> 2/3
DS2	Moderate damage: Cracks in partition and infill walls	D2–D3: medium—severe damage	< 1/3
			1/3–2/3
			> 2/3
DS3	Substantial-heavy damage: Large cracks in partition and infill walls, failure of individual infill panels	D4–D5: very heavy damage	< 1/3
			1/3–2/3
			> 2/3

Baggio et al. (2007) later proposed a more detailed (and quantitative) description of DSs for buildings, analyzing damage to vertical structures, floors, stairs, roofs and infills. Three damage grades were identified by Baggio et al. (2007): "D1"or Slight", "D2–D3" or Medium-Severe", and "D4–D5" or "Very heavy". About infills and partitions, "D1" and "D2–D3" are associated to cracks in infills less than 1 mm and from-1-to-5 mm width, respectively. Localised bricks expulsions can be found in "D2–D3". "D4–D5" is related to a partial or total collapse of the infill panel. A damage extent (DE) was also coupled with the damage severity. Three "ranges" of DE are identified in Baggio et al. (2007): less than 1/3 of the elements of the building; between 1/3 and 2/3 of all the buildings' elements and more than 2/3 of the building's elements, (see Table 1).

Based on these remarks, the correspondence between EMS-98 and Baggio et al. (2007) is reported in Table 1.

3 Proposed procedure to evaluate repair cost of infills and services

In this section the proposed methodology to evaluate Total Repair Cost (TRC) for RC buildings, considering infills and services, is described. The methodology presented herein belongs to the so-called "component-level" loss prediction procedures, similarly to Performance Assessment Calculation Tool (PACT) for probabilistic assessment of losses reported in FEMA P-58 (ATC 58. 2012a, b). As mentioned in Sect. 1, the PACT method starts from the results of a structural analysis. Then structural damage and economic losses are evaluated combining the analysis results with fragility functions and consequence data for a wide repository of structural and non-structural components. Unfortunately, no specific data (neither fragility functions or repair costs) related to infilled RC moment resisting frame buildings, widely used in Mediterranean area, are accounted for in the PACT tool (Cardone and Perrone 2015; Del Vecchio et al. 2018). The methodology presented herein aims to fill this gap, and to evaluate TRC for infilled RC buildings by using data specifically derived for this building typology. Only information about damage on infills/partitions are considered, being significant their contribution on damage analysis for the specific investigated structural typology, as highlighted by recent studies on this topic (Taghavi and Miranda 2003; Dolce and Goretti 2015; Del Gaudio et al. 2016; Del Vecchio et al. 2019). The information about damage on infills/partitions is thus used to evaluate the

repair costs due to the main repair activities for refurbishment of infills, partitions and for all services allocated in within, whose sum for all the components of the building provide its total repair costs. In fact, for residential Italian and Mediterranean RC buildings infilled with hollow clay bricks the repair costs for services can be related to damage of masonry panels, since the former are commonly located within the latter or closely interacting with them.

For the application of the loss estimation procedure, damage classification according to EMS-98 definition should be first performed (see Sect. 2). Then, repair costs due to infills (Sect. 3.1) and services (Sect. 3.2) should be evaluated. Thus, total repair costs due to both infill panels and services can be computed as a function of damage suffered by infills, as shown in Sect. 3.3.

3.1 Repair cost for infills and partitions

First, repair costs for infills and partitions have to be determined. To this aim, a list of elementary actions to be performed for a given DS is fixed, determining the main operations required to repair infills/partitions. Then, the repair cost at each DS_i (with i = 1, 2, 3) can be calculated by summing up the products of all the unit costs (c_j) for each elementary action multiplied by the relevant area of intervention ($A_{j,DSi}$). In what follows, the Price List of Public Works in Abruzzi Region (B.U.R.A. 2017) has been used to define such unit costs, coherently with the validation of the methodology later shown in Sects. 4 and 5. Anyway, every other definitions of unit costs can be used for other applications.

Table 2 reports both the unit costs (c_j) and the relevant area of intervention ($A_{j,DSi}$) considering seven different activity groups (from "*a*" to "*g*") and the specific elementary actions required for each of them.

Double leaf cavity masonry walls representative of typical existing RC infilled buildings in the Mediterranean area are considered in this study. They are assumed as constituted by (12×25×25) cm hollow clay bricks (with a void percentage > 55%) for exterior leaf, and (8×25×25) cm hollow clay bricks (with a void percentage > 55%) for interior leaf, with thermal insulation, as typical of the Mediterranean area (Bal et al. 2008). This assumption is also valid for RC buildings struck by L'Aquila (2009) earthquake (Ricci et al. 2011) that will be analysed in next sections. The repair cost ($\bar{C}_{DSi}^{Infills}$) for this panel typology—hereinafter referred to (hollow + hollow) panel—at the damage state DS_i, can be evaluated as shown in Eq. (1):

$$\bar{C}_{DSi}^{Infills} = \sum_{j}^{\{a,b,c,d,e,f,g\}} (c_j \cdot A_{j,DSi}) \tag{1}$$

Note that c_j and $A_{j,DSi}$ reported in Table 2 descend from those reported in Del Gaudio et al. (2019b) with some modifications. Firstly, only three DSs are considered herein, i.e., those related respectively to the *light cracking damage pattern*, the *extensive cracking damage pattern*, the *total infill collapse/failure condition* (Del Gaudio et al. 2019b). Thus, the damage state related to the "economically convenience" *limit to repair without demolish/ reconstruct* has been discarded in this work, since it differs from the *total infill collapse/ failure condition* only for what concern the inter-story drift ratio (IDR) capacity, being substantially equal the corresponding c_j and $A_{j,DSi}$. Moreover, the repairing actions related to *removal of solid wood frame, box and roller shutter* and *installation of old window or door*

Table 2 Unit cost and extension of repair areas for assumed elementary actions for infills according to B.U.R.A. (2017)—adapted from Del Gaudio et al. (2019b)

Activity group	Elementary actions	Unit	Unit cost (c_j)	$A_{j,DS1}$	$A_{j,DS2}$	$A_{j,DS3}$
(a) Preliminary operations	Install scaffolding with steel scaffolding and multi-directional ringlock rosettes [...]	€/m²	25.72	$(H_w \times L_w)$	$(H_w \times L_w)$	$(H_w \times L_w)$
(b) Demolition activities	1. Demolition of single leaf masonry brick with mechanical equipment	€/m²	13.84	–	10% $(H_w \times L_w)$	$(H_w \times L_w)$
	2. Render or plaster removal up to 5 cm thick (including surface brushing of affected area)	€/m²	8.58	$(0.20 \text{ m}) \times d^c$	30% $(H_w \times L_w)$	$(H_w \times L_w)$
(c) Construction activities	1. Construction of infill panels: (i) Construction of double leaf cavity masonry wall (12×25×25 hollow clay brick for exterior leaf and 8×25×25 hollow clay brick for interior leaf)	€/m²	72.58	–	10% $(H_w \times L_w)$	$(H_w \times L_w)$
	2. Cavity thermal insulation with Glass mineral wool	€/m²	22.78			
(d) Finishings	1. Coat rendering or plastering (3 layers) with cement mortar	€/m²	23.86	$(0.20 \text{ m}) \times d$	$(30+10)\% (H_w \times L_w)$	$(H_w \times L_w)$
	2. Water-based primer application	€/m²	2.53	$(H_w \times L_w)$	$(H_w \times L_w)$	$(H_w \times L_w)$
	3. Coating painting (3 layers) for each side with water-based paints	€/m²	13.19	$(H_w \times L_w)$	$(H_w \times L_w)$	$(H_w \times L_w)$

Table 2 (continued)

Activity group	Elementary actions	Unit	Unit cost (c_j)	$A_{j,DS1}$	$A_{j,DS2}$	$A_{j,DS3}$
(e) Windows or door frame installation	1. Installation of new or old window or door opening					
	(i) Installation of new window or door opening with solid wood frame with douglas [...]	€/m²	542.6	–	–	$(H_{op} \times L_{op})^a$
	(ii) Installation of old window or door opening with solid wood frame and rolling shutter and glazing replacement	€/m²	125.9	–	$(H_{op} \times L_{op})^a$	–
	2. Removal of solid wood frame, box and roller shutter	€/m²	34.12	–	$(H_{op} \times L_{op})^a$	$(H_{op} \times L_{op})^a$
(f) Landfill	1. Landfill transportion	€/m³	26.24	$(0.20\ m) \times d \times (0.10\ m)$	$30\%(H_w \times L_w) \times (0.10\ m) + 10\%(H_w \times L_w) \times (s^b + 0.10\ m)$	$(H_w \times L_w) \times (s + 0.10\ m)$
	2. Landfill disposal^a	€/t	15.18			
(g) Technical cost	Technical cost	%	8.00	$\sum_j^{\{a,b,c,d,e,f\}} c_f A_{j,DS1}$	$\sum_j^{\{a,b,c,d,e,f\}} c_f A_{j,DS2}$	$\sum_j^{\{a,b,c,d,e,f\}} c_f A_{j,DS4}$

^{a}H_{op} and L_{op} are the height and length of the opening, respectively

^{b}s = infill thickness

^{c}d = infill diagonal

Table 3 Repair costs for double leaf hollow clay bricks ($\bar{C}_{DSi}^{Infills}$ per infill surface unit (obtained from the application of unit costs and extension relative to the activity groups of Table 2)

	$\bar{C}_{DS1}^{Infills}$ (€/m²)	$\bar{C}_{DS2}^{Infills}$ (€/m²)	$\bar{C}_{DS3}^{Infills}$ (€/m²)
Solid panel	77.0	105.3	285.8
Panel with window	73.0	118.76	331.4
Panel with door	69.2	131.55	374.9

opening with solid wood frame and rolling shutter and glazing replacement are included herein, according to suggestions reported in Del Vecchio et al. (2019).

Hence, $\bar{C}_{DSi}^{Infills}$ has been evaluated for three panel typologies: "solid" (i.e., without openings), "with window opening" and "with door opening", following a Monte Carlo simulation technique, considering a number of realizations (N = 1000) varying the infill dimensions in typical ranges. Therefore, infill length, L_w, is assumed to vary from 4.00 to 5.00 m; the infill height is assumed, on average, equal to $H_w = 2.75$ m; openings are considered as constituted by wood frames with dimensions of (0.90×1.50) m² or (1.20×2.20) m² for window or door opening, respectively.

As a result, the repair cost $\bar{C}_{DSi}^{Infills}$ for each panel typology at DS_i (i = 1,…,3) are reported in Table 3. A dispersion around these values may be considered due to variability related to different professional practices or to different unit costs in different geographical areas or considering uncertainty in contractor pricing strategies. However, this aspect is not considered herein and does not limit the presented methodology.

Additionally, it has been assumed that interior infill partitions are made up of $(8 \times 25 \times 25)$ cm hollow clay bricks with cement mortar. The corresponding repair costs, $\bar{C}_{DSi}^{Partitions}$, for different damage states are evaluated starting from those of (hollow + hollow) clay brick panel, $\bar{C}_{DSi}^{Infills}$, by simply subtracting/adding some specific activities as reported in Table 4.

Repair costs related to infills and partitions provided in Tables 3 and 4 are specific costs for infill panel surface unit. However, a very useful information for more rapid loss estimations certainly is the knowledge of repair costs of infills and partitions (IP) per floor surface unit (C_{DSi}^{IP}). Obviously, C_{DSi}^{IP} depends on the ratio between total infill surface area at each floor and the floor plan area (A) and should be determined case-by-case. To overcome this case-specific limitation, herein a Montecarlo simulation is applied with N = 1000 simulations, assuming some hypotheses, quite common in existing RC infilled buildings, based on the analysis of data presented in the following applications (discussed in Sect. 5):

- the floor Plan Ratio (PR), i.e., longitudinal side (L_x)-to-transverse side (L_y) ratio, can vary between 1 and 2.5 (with a uniform probability distribution) (Del Gaudio et al. 2017);
- plan area (A) varies within the range [70; 250] m² with a uniform probability distribution;
- The presence of openings is assumed as a uniform discrete RV among the cases "solid" panel, panel "with window opening" and panel "with door opening";
- The total linear length of interior partitions ($L_{int,x}$ and $L_{int,y}$) along the two main orthogonal directions (x and y) of the building is obtained in the hypothesis that the geometric percentage of interior infills was equal to the 50% of the geometric percentage of exterior infills (as suggested in Bal et al. 2008; Del Gaudio et al. 2017). It is also assumed that the thickness of external ($t_w^{Infills}$) and interior ($t_w^{Partitions}$) infill panels are equal to 200 and 80 mm, respectively.

Table 4 Definition of the repair cost for interior infill partitions starting from the costs of exterior infills according to B.U.R.A. (2017)

	$\bar{C}^{Partitions}_{DS1}$ (€/m²)	$\bar{C}^{Partitions}_{DS2}$ (€/m²)	$\bar{C}^{Partitions}_{DS3}$ (€/m²)
(Hollow + hollow) solid panel exterior infill	77.0	105.3	285.8
Subtract			
Scaffolding with steel scaffolding and multi-directional ringlock rosettes, with Fiberglass Monofilament Netting for scaffolding enclosure	25.7	25.7	25.7
Demolition of single leaf masonry brick with mechanical equipment	–	1.4	13.8
Construction of double leaf cavity masonry wall (12×25×25) cm hollow clay brick for exterior leaf and (8×25×25) cm hollow clay brick for interior leaf	–	7.3	72.6
Add			
Interior infill partition with cement mortar and (8×25×25) cm hollow clay bricks	–	2.6	26.3
Interior partition with hollow clay bricks	51.3	73.5	199.9

Given these hypotheses, the exposed infill area per each floor ($S'_{Infills}$) and the exposed partition area per each floor ($S'_{Partitions}$), can be evaluated as in Eqs. (2a) and (2b):

$$S'_{Infills} = 2 \cdot (L_x + L_y) \cdot h \tag{2a}$$

$$S'_{Partitions} = (L_x + L_y) \cdot h \cdot t_w^{Infills} / t_w^{Partitions} \tag{2b}$$

where L_x, L_y, $t_w^{Infills}$, and $t_w^{Partitions}$ have been defined above, and h is the inter-story height. Thus, if the whole exposed infill area in a given storey is characterised by damage DS_i (with i = 1, 2, 3), C_{DSi}^{IP} can be calculated as in Eq. (3). Mean, 50th (median), 16th, and 84th percentiles (prctile) of costs C_{DSi}^{IP} obtained in such a way are reported in Table 5, along with their standard deviation (std).

$$C_{DSi}^{IP} = \frac{\bar{C}_{DSi}^{Infills} \cdot S'_{Infills} + \bar{C}_{DSi}^{Partitions} \cdot S'_{Partitions}}{A} \tag{3}$$

3.2 Repair cost for Services

Repair costs for services are determined, considering four different activity groups, namely: (1) plumbing and (2) electrical systems, (3) radiators and (4) roof/wall tiles. As for infills/partitions, the Price List of Public Works in Abruzzi Region (B.U.R.A. 2017) was used also for services. Moreover, the corresponding costs for technicians and those for landfill transportation and disposal are also considered.

As anticipated before, repair activities for services have been associated to damage suffered by infill panels, since services are generally allocated within infills in residential RC buildings in the Mediterranean region. Therefore, it is assumed herein that if infills are characterized by several diagonal cracks for an extensive panel area (DS2), some water pipes of distribution systems could break or some of sanitary equipment could crack, thus requiring their refurbishment. In addition, the restoration of water and/or wastewater distribution system requires the removal of old floor/wall tiles, the installation of screed layer, the supplying and installation of floor/wall tiles for bathroom. Obviously, if infill panels completely collapse (DS3), all services (partially or totally) allocated in within, namely plumbing and electrical systems, and radiators, have to be re-installed after the construction of the new infill panels. Moreover, it is also assumed that the collapse of infills could produce cracks in the floor tiles requiring their removal, along with the screed layer, their supplying and re-installation.

Table 5 Repair costs for infills and partitions per plan surface unit

Infills + partitions	C_{DS1}^{IP} (€/m^2)	C_{DS2}^{IP} (€/m^2)	C_{DS3}^{IP} (€/m^2)
Mean	142.1	224.1	485.5
Median	135.0	213.1	462.8
16th prctile	102.8	156.2	325.8
84th prctile	105.7	159.5	332.7
Std	26.6	43.4	98.8

Table 6 Unit costs for elementary repairing actions regarding services according to B.U.R.A. (2017)

Activity group	Elementary actions	Unit	Unit cost (c_j)	$A_{j,DS1}$	$A_{j,DS2}$	$A_{j,DS3}$
(a) Plumbing system	1. Sanitary equipment removal:					
	(i) Bidet	€/each	70.52		✓	✓
	(ii) Water closet		70.52		✓	✓
	(iii) Shower base		56.04			
	(iv) Wash Basins		54.17			
	2. Sanitary equipment supplying and installation (including fixture supply pipes):					
	(i) Bidet (including faucet)	€/each	490.0		✓	✓
	(ii) Water closet		376.8			
	(iii) Shower base (including faucet)		500.5			
	(iv) Wash Basins (including faucet)		670.5			
	1. Other equipments:	€/each				
	(i) Kitchen Sinks removal		54.17		✓	✓
	(ii) Kitchen Sinks supplying and installation (including faucet)		499.4			
	(iii) Washing machine set-up		102.9			
	2. Bathroom water distribution system	€/each	527.3		✓	✓
	3. Bathroom wastewater system including the outside waste pipes installation	€/each	518.8		✓	✓
	4. Hot water heater	€/each	1069.9		✓	✓
(b) Radiators	1. Supplying and installation of radiator	€/each	311.7			✓
	2. Supplying and installation of radiator for bathroom	€/each	263.9			✓
(c) Electrical system	1. Power socket supplying and installation	€/each	34.22			✓
	2. Electrical switch supplying and installation	€/each	23.66			✓
	3. Ceiling light set-up	€/each	21.9			✓
	4. Tv socket supplying and installation	€/each	64.3			✓
	5. Telephone outlet supplying and installation	€/each	21.9			✓
	6. Electric panel and electric backbone	€/each	350.8			✓
	7. TV antenna/aerial	€/each	124.1		✓	✓
(d) Floor/wall tiles	1. Removal of old floor tiles	€/m²	8.7			✓

Table 6 (continued)

Activity group	Elementary actions	Unit	Unit cost (c_j)	$A_{j,DS1}$	$A_{j,DS2}$	$A_{j,DS3}$
	2. Installation of screed (including the supplying of materials)	€/m²	15.7			✓
	3. Supplying and installation of floor tiles	€/m²	48.6			✓
	4. Removal of old wall tiles (for bathroom only)	€/m²	7.0		✓	✓
	5. Supplying and installation of wall tiles (for bathroom only)	€/m²	54.6		✓	✓
(e) Landfill	1. Landfill transportion	€/m³	26.24		✓	✓
	2. Landfill disposal*	€/t	15.18			
(f) Technical cost	Technical cost	%	8.00		✓	✓

The association between the repair activities for services and infills DSs is reported in Table 6 (5th to 7th columns), along with the unit costs for each required elementary action evaluated from B.U.R.A. (2017).

Generally speaking, the quantification of each single item reported in Table 6 requires a detailed analysis of architectural plan disposal to achieve a detailed estimate of the number of sanitary equipment to install, the number of power sockets or electrical switches required, the amount of wall/floor tiles to lay. Unfortunately, such a detailed kind of information is not always available, especially for a large-scale loss estimation that deals with large amount of data.

To overcome this limitation, a simplified approach is proposed herein, considering that the dwelling can be subdivided into two different "ideal room" typologies, as reported in Fig. 1: generic room and bathroom. Different repair activities have been required for the considered room typologies. In fact, those related to the bathroom need additional activities respect to a generic room, basically related to the plumbing system (elementary action a.1 to a.5 of Table 6) and those related to refurbishment of wall tiles, in addition to the common activities (electrical system, radiators, refurbishment of floor tiles) required also for all the other room typologies.

Then, the quantification of each single feature reported in Table 6 for these two "ideal rooms" is firstly done. For example, for a generic room, 4 power sockets, 1 electrical switch and 1 ceiling light, 1 TV socket, 1 telephone outlet, 1 radiator, removal of floor tile, of the screed layer, supplying and re-installation of new floor tile for the corresponding surface area are considered. On the other hand, for the bathroom, the considered activities are: 2 power sockets, 2 electrical switch and 2 ceiling light installation; 1 radiator installation; the installation of water and wastewater distribution systems (including the installation of the

Room

$L'^{room}_x = 3.0 \div 4.5m$

$L'^{room}_y = 3.0 \div 4.5m$

Services repair activity groups:
- Electrical system (b.1-b.5);
- Floor tiles (d.1-d.3);
- Radiators (e.1)

Bathroom

$L'^{bath}_x = 1.7 \div 3.0m$

A^{bath}/L'^{bath}_x

Services repair activity groups:
- Plumbing system (a.1-a.5);
- Electrical system (b.1-b.3);
- Floor tiles (d.1-d.5);
- Radiators (e.2)

$A^{bath} = 3.5 \div 5.0 \ m^2$

$w^{bath} = \dfrac{A^{bath}}{L'_x \cdot L'_y} = 0.05 \div 0.10$

$$trc^{services}_{DS_i} = \frac{TRC^{room}_{DS_i}}{A^{room}} \cdot \left(1 - w^{bath}\right) + \frac{TRC^{bath}_{DS_i}}{A^{bath}} \cdot w^{bath} + \frac{TRC^{general\_system}_{DS_i}}{L'_x \cdot L'_y}$$

Fig. 1 Conceptual representation of repair activities for services refurbishments and definition of weights for "ideal room" typologies

outside waste pipes); the removal, supplying and installation of new sanitary equipment (1 Bidet, 1 Water closet, 1 Shower base, 1 Wash Basins, including faucets in all cases); removal of floor tile, of the screed layer, supplying and re-installation of new floor tile for the corresponding surface area; the removal, supplying and re-installation of wall tile for a height of 2.1 m.

Hence, the plan dimensions for both the ideal room typologies and their weights (evaluated as the ratio of their area over the entire dwelling surface) have been defined through the introduction of the random variables (RVs) listed below:

- room plan dimensions (L'^{room}_x and L'^{room}_y), assumed as a continuous RV within the range [3.0; 4.5] m (Fig. 1), based on Italian Health Ministery Decree of 5 July 1975 (D.M. 75);
- minimum dimension of bathroom (L'^{bath}_x) and its plan area (A^{bath}), assumed as a continuous RV within the ranges [1.7; 3.0] m and [3.5; 5.0] m², respectively (Fig. 1) (D.M. 75);
- the percentage incidence (or "weight") of A^{bath} (w^{bath}) with respect to the plan area of the whole dwelling assumed as a continuous RV within the range [0.05; 0.10] (D.M. 75).

Lastly, repair cost for services at DS_i, $C^{services}_{DS_i}$, is evaluated by averaging the repair costs related to the two "ideal rooms" on the whole dwelling surface by using their weights with respect to the total dwelling area. To this aim, $C^{services}_{DS_i}$ is evaluated using a Monte Carlo simulation technique, considering a number of $N = 1000$ realizations, as a function of the random variables listed above, according to Eq. (4):

$$C^{services}_{DS_i} = \frac{C^{room}_{DS_i}}{A^{room}}\left(1 - w^{bath}\right) + \frac{C^{bath}_{DS_i}}{A^{bath}}w^{bath} + \frac{C^{general\_services}_{DS_i}}{(L'_x L'_y)} \tag{4}$$

where the weight of bathroom is taken equal to $w^{bath} = A^{bath}/(L'_x L'_y)$, and the weight of a generic room is equal to $(1 - w^{bath})$. The costs related to 1 Hot water heater, 1 Electric panel and electric backbone, 1 TV antenna/aerial, $C^{general\_services}_{DS_i}$, are considered for the entire dwelling and thus divided only by the total dwelling surface area ($L'_x L'_y$).

The resulting costs for services are reported in Table 7.

Table 7 Costs for services at each DS

| All services (Activity group from "a" to "e")	$C^{services}_{DS1}$ (€/m²)	$C^{services}_{DS2}$ (€/m²)	$C^{services}_{DS3}$ (€/m²)
Mean	0.0	128.8	258.9
Median	0.0	127.1	256.0
16th prctile	0.0	75.5	185.9
84th prctile	0.0	77.8	191.2
Std	0.0	28.2	32.8

3.3 Total repair cost evaluation

The methodology to evaluate the TRC for infilled RC buildings follows the flowchart reported in Fig. 2. The input parameters are represented by:

- repair costs for infills and services, and
- information about damage severity, DS_i, and its extent, DE_{DSi}, at each DS_i ($i = 1, 2, 3$) on infills/partitions.

Fig. 2 Flowchart of the methodology for total repair cost evaluation
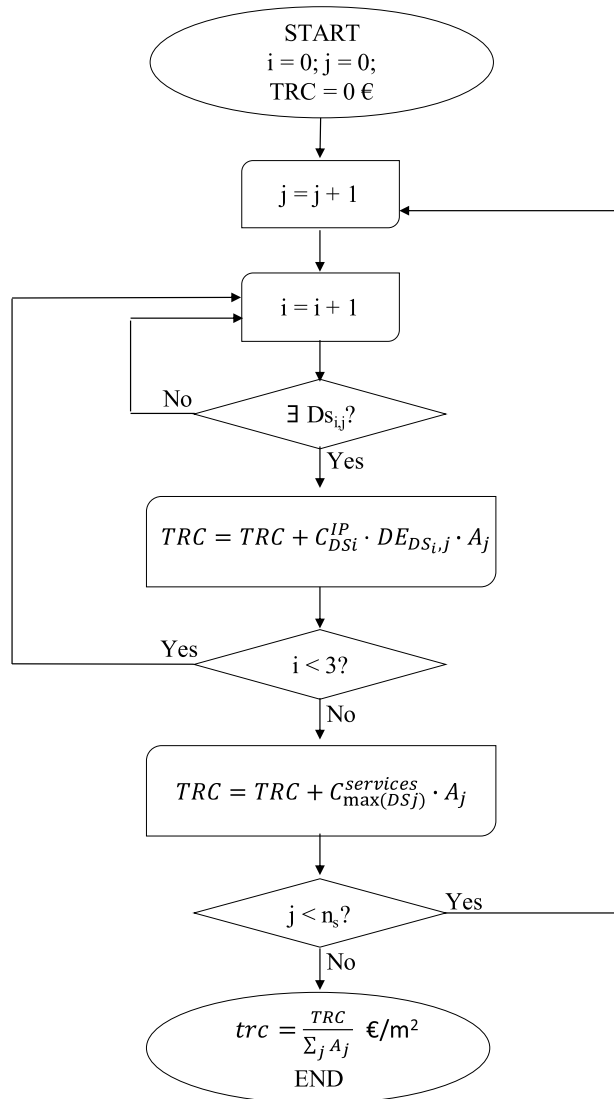
Costs for infills and services can be found in Sect. 3.1 and 3.2, respectively; information about damage severity and extent for a given building can be determined through of structural analysis or by means of data collected after post-earthquake inspections. The latter circumstance will be used in the validation phase of the procedure presented in Sects. 4 and 5.

Obviously, if no damage is observed on infills/partitions, the methodology early ends resulting in a null value for TRC. On the contrary, if at least one of the possible damage levels is observed on infills/partitions, the methodology starts with the evaluation of TRC. Moreover, different damage severity levels and extents can be attained in a building, in different parts/stories of the building. For example, a very heavy damage level for infills at the bottom stories can co-exists with a slight damage level for intermediate storeys and no damage for upper storeys. Therefore, the methodology allows summing up the repair costs of the infills/partitions characterized by DS_i (i = 1, 2, 3) by simply introducing a "for-loop", by repeating the calculation three times for each storey (j-index in Fig. 2). If no infills are characterized by DS_i (i = 1, 2, 3) their contribution is not considered for the TRC evaluation; otherwise the contributions of repair activities related to infills/partitions for the relevant quantities will be added to TRC.

Then, the costs due to services have to be added to costs due to infills. To this aim, the maximum DS ($\max(DS_j)$) achieved by infills at each storey is assumed to determine the repair activities for services, as shown in Fig. 2. Note that repairing activities related to services are reasonably extended not only to the area closest to the damaged infill panels, but to the whole storey (with plan area A_j) where a given DS is attained, to guarantee a proper spatial continuity of the repairing activities (such as floor tiles replacement, for example).

In other words, the Total Repair Cost, TRC, can be evaluated as the sum, for all the storeys, of repair costs due to infills/partitions at each DS_i (for i = 1, 2, 3), and repair costs due to services related to the maximum DS achieved storey-by-storey, as in Eq. (5a). Lastly, the specific total repair cost per plan area (*trc*) is evaluated as the ratio between TRC and the total plan area of the building (Eq. 5b).

$$TRC = \sum_{j=1}^{n_s} \sum_{i=0}^{3} C_{DSi}^{IP} \cdot DE_{DSi,j} \cdot A_j + \sum_{j=1}^{n_s} C_{maxDSj}^{services} \cdot A_j \tag{5a}$$

$$trc = \frac{TRC}{\sum_{j=1}^{n_s} A_j} \tag{5b}$$

It is worth noting that, for long-term prediction purposes, inflation in material prices should be considered, too, by assuming an inflation prediction model in the estimation of each necessary unit cost. However, this aspect is not investigated in the present work and does not limit the methodology and the following predicted-versus-actual costs comparisons since inflation was almost null in the reference time period for the following application (De Martino et al. 2017).

4 Validation by means of case-study buildings

The procedure described in Sect. 3 is applied to evaluate the repair costs for some specific case-study buildings. These case studies are real buildings (described in more detail in Sect. 4.1), struck by L'Aquila (Italy) 2009 earthquake, for which a significant amount of detailed data has been collected during post-event reconnaissance field trips. Additionally, their damage and actual repair costs are also known in detail (Del Vecchio et al. 2018), and, thus, they can represent an important testbed for the validation of the methodology proposed herein. The comparison between predicted and actual *trc* is finally shown and discussed in Sect. 4.2.

4.1 Description of case-study buildings

The case-study buildings analyzed in this section were struck by the L'Aquila (Italy) earthquake (April 6th, 2009), a seismic event of 6.3 magnitude, resulting in IX–X grade of MCS macro-seismic scale. The main features of the event can be found in Chioccarelli et al. (2009).

Buildings selected for the purposes of this section have been previously collected and analyzed by Del Vecchio et al. (2018). They are RC moment resisting frame buildings with masonry infills for which the post-earthquake damage analysis is available. Additionally, they are well-representative of a wider database of damaged buildings related to the same seismic event (Del Vecchio et al. 2018).

More in details, buildings B1, B2 and B3, presented in Del Vecchio et al. (2018), are analyzed, since they mainly exhibited damage to infills and partitions (and very low or null damage to vertical structures, stairs and floors…). Therefore, they can represent a testbed closer to the loss assessment methodology proposed in Sect. 3, which does not account for structural components to assess seismic losses. Their main features are summarised in Table 8. Number of stories, average plan area and plan aspect ratio (PR) are obtained from the plan longitudinal and transverse dimensions reported from the explicit drawings in Del Vecchio et al. (2018).

Damage severity and extent were well-documented by photos and descriptions. In particular:

- case-study B1 presented a concentrated very heavy damage (DS3) to few infills and a more widespread (in more than 2/3 of the building) slight damage (DS1);
- case-study B2 exhibited a very heavy damage (DS3) to infills and partitions in a significant portion (between 1/3 and 2/3) of the building;
- lastly, building B3 presented moderate-severe (DS2) damage and very heavy (DS3) damage to infills, and, additionally, some concentrated damage to the vertical structure (in one beam-column joint).

Table 8 Main features of the analysed case-study buildings

Case-study ID	Average plan area (m^2)	PR (–)	N. of stories (–)	DE to infills/partitions (–)	DE to vertical structures (–)	Actual trc (€/m^2)
B1	180	1.65	4 + 1[a]	DS3]0;1/10] DS1 [2/3;1]	–	212.1
B2	120	1.67	3	DS3]1/3;2/3]	–	453.4
B3	160	1.70	4 + 1[a]	DS3]0;1/3] DS2]1/3;2/3]	Medium-Severe]0;1/3]	396.8

[a]"+1" = a floor-basement-story exists

Damage severity and extent has been reported in Table 8. It should be mentioned that, in the building B1, a very small number of infill panel was interested by DS3 damage level; therefore, such a (qualitative) information has been herein converted in a numerical data assuming that less than 10% of the exposed infill area had DS3 damage. Actual trc for these buildings according to Del Vecchio et al. (2018) are also shown in Table 8.

4.2 Estimation of *trc* and comparison with the actual *trc*

Data described in Sect. 4.1 have been used for the repair costs prediction, to be compared with the actual trc. Therefore, the whole procedure explained in Sect. 3 is applied. Additionally, the damage extent has been assumed as a continuous Random Variable (RV) with a uniform probability density function within the ranges of damage extent provided for each building and each DS (in Table 8). As a result, the *predicted trc* are shown in Table 9 and compared with the *actual trc*.

Mean predicted-to-actual trc results very close to the unity, with very slight errors for buildings B1 and B2 (− 2% and − 3%, respectively). On the other hand, a higher error (− 13%) is obtained for building B3, since the latter exhibited medium-severe damage also to vertical structures. As a matter of fact, since the methodology presented herein for trc evaluation accounts for repair activities concerning infills/partitions and services, only, the predicted value slightly underestimates the actual trc.

Therefore, when a significant damage to vertical structures, or in general to other components, is observed, the methodology slightly underestimates trc, neglecting their contributions. On the other hand, for those buildings where demolition and reconstruction are required, this methodology could be easily integrated considering the nominal cost of construction per cubic meter of RC structures and the total volume occupied by buildings, as, for example, reported in Cardone (2016).

Table 9 Predicted versus actual *trc* for the analysed case-study buildings

Case-study ID	Actual trc (€/m^2)	Predicted trc (€/m^2)	Predicted/Actual trc (–)
B1	212.1	208.1 ± 50.4[a]	0.98[b]
B2	453.4	438.1 ± 60.7[a]	0.97[b]
B3	396.8	344.9 ± 105.6[a]	0.87[b]

[a]Mean ± standard deviation

[b]Ratio related to the mean predicted value

5 A large-scale validation by means of a "ligthtly damaged" building stock

A further validation of the methodology described in Sect. 3 is carried out, by considering a wider dataset of infilled RC buildings. L'Aquila (Italy) 2009 earthquake is considered also in this case, since for this seismic event a significant amount of useful and extensive data has been collected during post-event reconnaissance field trips.

The building stock considered for this further step of validation was located in the epicentral area, covering about fifty municipalities. After the seismic event, it was interested by an extensive post-earthquake data collection to judge about their usability and damage level, mainly resulting damaged to infills and partitions with very slight or null damage to structural components. A preliminary analysis of these data has been already presented in De Risi et al. (2019), relating to the contribution of infills only, pointing out that predicted costs were about 50% of the actual costs. In this section, data collected for such a building stock are first briefly presented in Sect. 5.1. Repair costs are predicted, considering both infills and services, and analysed (Sect. 5.2). Lastly, predicted costs are compared with actual repair costs (Sect. 5.3) available from studies from literature (Dolce and Manfredi 2015) to show their (small) difference and stress the reliability of the loss estimation proposal for large-scale applications.

5.1 Building stock description and damage data from post-earthquake reconnaissance field trips

Post-earthquake reconnaissance field trips can provide useful information about suffered damage level. After L'Aquila earthquake, a significant effort was carried out for the systematic assessment by visual inspection of damaged buildings to decide about their usability rating or, eventually, the interruption of their use. Such inspections were performed by means of proper forms, the so-called "AeDES" forms (Baggio et al. 2007). Their output have been later recently published by the Italian Department of Civil Protection (DPC) on an online (Da.D.O.) platform (Dolce et al. 2019a), providing useful data about damaged buildings in the Abruzzi region. The main data obtained from this platform are synthetically reported herein, since they represent the base for the application of the methodology to this dataset.

First, the post-earthquake forms collected information about:

- building location,
- construction typology (masonry or RC),
- age of construction,
- main geometrical properties: storey number (n_s), average story height (h) and average plan area (A),
- building's use.

Additionally, information about the damage severity ("Null"; "D1—Slight", "D2–D3—Medium-Severe", "D4–D5—Very heavy") and extent (< 1/3, 1/3–2/3, > 2/3 of the whole building) is reported for vertical structures, floors, stairs, roof, infills and partitions or pre-existing damage (as commented in Sect. 2). Damage severity is defined according to the European Macroseismic Scale (Grunthal 1998) (see Sect. 2).

Finally, the forms provide a usability rating (UR) for each building among the following: "A" (usable building), "B" (temporary unusable), "C" (partially unusable), "D" (additional investigation required), "E" (unusable building), "F" (external risk sources).

It is worth mentioning that damage data officially released in Da.D.O. platform are herein considered without any further refinements. Their reliability is ensured by: (1) the introduction of mandatory short-courses before any survey campaign for training of inspectors on compilation of survey form (namely, the above-mentioned AeDES form), and (2) by a prompt validation procedure of each form taking advantage of the correlation between damage and usability outcomes.

The building stock investigated in this section is an extract of the whole dataset available in Da.D.O. platform. First, only residential RC infilled framed buildings have been selected. Among them, buildings with damage to infills/partitions only are considered (namely no damage exists for vertical structures, horizontal structures, stairs, roofs). In such a way, the application of the methodology described in Sect. 3, which does not account for eventual structural damage, should be able to provide *predicted trc* very close to the *actual trc*.

Such a subset of buildings can be defined as "lightly damaged" building stock, and, overall, it includes 5095 buildings. Its main features are reported in Fig. 3 in terms of:

- suffered PGA range during L'Aquila 2009 mainshock (obtained from the shake-map of the event published by National Institute of Geophysics and Volcanology according to the procedure reported in Michelini et al. 2008),
- average plan area (A) ranges (average value among all stories),
- number of stories (n_s),
- age of construction ranges.

A significant percentage of the analysed buildings suffered a quite severe seismic shaking: 77% of buildings were subjected to a peak ground acceleration (PGA) ranging between 0.30 and 0.50 g. About 75% of the building stock has 3 or 4 stories. A significant percentage of them (almost 73%) was built after 1982, namely—considering their location in a very seismic prone area—they were likely designed to sustain (slight) seismic action, but according to obsolete code prescriptions.

The data collected in Da.D.O. platform allow also obtaining the damage severity and extent for each building, in agreement with the damage metric reported and commented in Sect. 2. Therefore, for the investigated dataset, it was observed that (see Table 10):

- 2406 (/5095) buildings presented no damage at all: their maximum damage level was DS0;
- 1943 (/5095) buildings presented a maximum damage level "D1- Slight", characterized by different extent (81.9% of them for an extent < 1/3 of the whole building; 15.4% for an extent ranging between (1/3 and 2/3) of the building; the remaining 2.7% for a higher extent, i.e. > 2/3 of the whole building. Therefore, such buildings are considered as characterized by a maximum damage level DS1;
- 555 (/5095) buildings presented a maximum damage "D2–D3—Medium-Severe", and, therefore, they belong to the DS2—classified buildings. For DS2—buildings, too, different extent of damage can be observed: 52.3% of them have DS2 damage to infills in less than 1/3 of the building; 33.9% and 13.9% in (1/3-2/3) or > 2/3, respectively, of the whole building;
- 191 buildings (i.e., 3.7% of whole building stock) have a maximum damage DS3, in the major part of the cases with an extent lower than 2/3 of the whole building.
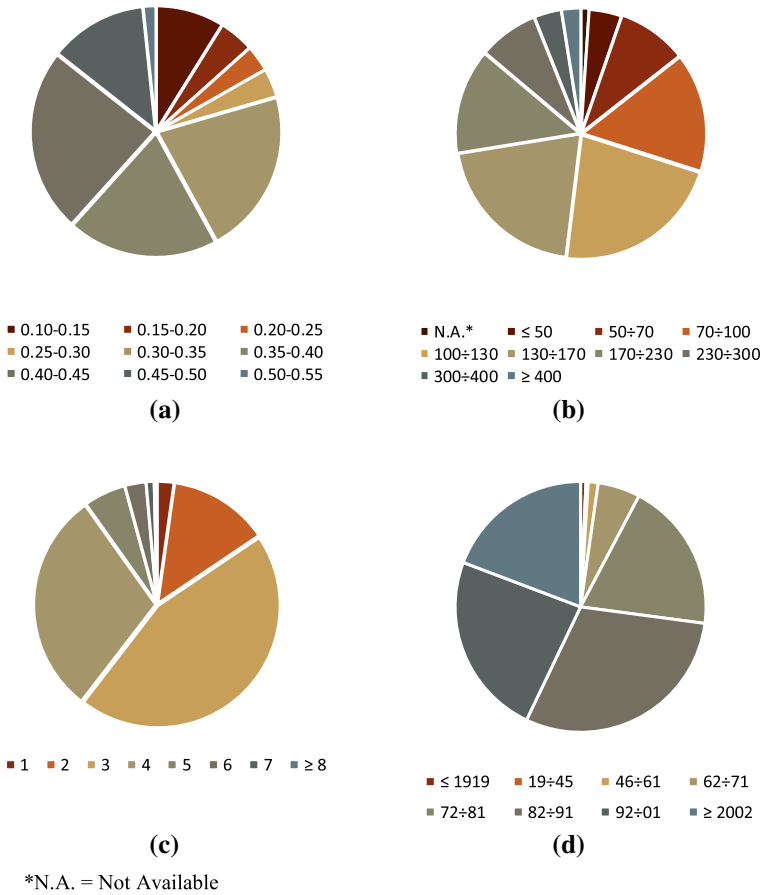
Fig. 3 Main features of the selected building stock: PGA (in g) (**a**), plan average area (in m^2) (**b**), number of stories (**c**), and age of construction (**d**). *N.A.* not available

Table 10 Number and percentage of buildings belonging to the analysed dataset depending on the maximum observed DS from AeDES forms

Maximum observed DS	DS0	DS1	DS2	DS3
Number of buildings	2406	1946	555	191
Buildings percentage (%)	47.2	38.1	10.9	3.7

Additionally, if DS$_i$ is the maximum damage level for a given building, a certain extent of damage DS$_j$ with (j < i) can exist. This additional information has been also collected for the investigated building stock, since necessary for a more realistic application of the loss prediction methodology.

5.2 Prediction of *trc* for a building stock

Data and observed damage information commented in Sect. 5.1 are used herein to predict the *trc* related to the whole building stock by means of the methodology explained in Sect. 3.

Some details about the application of the methodology are necessary when managing with post-earthquake inspection forms at large-scale, as in this case, since information on damage severity and extent are not discriminated for each storey. In this case, an average measure of damage for the whole building (at each DS) is known and an "adjustment" of the flowchart in Fig. 2 is needed, both for infills and for services contributions.

Therefore, when damage severity and extent are not known storey-by-storey, Eqs. (5a) and (5b) can be simplified as shown in Eqs. (6a) and (6b):

$$\text{TRC} = A \cdot \left[\sum_{i=0}^{3} \bar{n}_i \cdot \left(C_{\text{DSi}}^{\text{IP}} + C_{\text{DSi}}^{\text{services}} \right) \right] = A \cdot n_s \left[\sum_{i=0}^{3} \text{DE}_{\text{DSi}} \cdot \left(C_{\text{DSi}}^{\text{IP}} + C_{\text{DSi}}^{\text{services}} \right) \right] \quad (6a)$$

$$\text{trc} = \frac{\text{TRC}}{n_s \cdot A} = \left[\sum_{i=0}^{3} \text{DE}_{\text{DSi}} \cdot \left(C_{\text{DSi}}^{\text{IP}} + C_{\text{DSi}}^{\text{services}} \right) \right] \quad (6b)$$

where:

- A and n_s are the average plan area and the number of stories, respectively, as explained before;
- $\bar{n}_i$ returns an approximation of the number of storeys affected by the ith DS and it is obtained as the product between DE_{DSi} and the total number of storeys, n_s, namely $\bar{n}_i = \text{DE}_{\text{DSi}} \cdot n_s$;
- $C_{\text{DSi}}^{\text{IP}}$ and $C_{\text{DSi}}^{\text{services}}$ are repair costs per floor unit for infills/partitions and services reported in Tables 5 and 7, respectively.

Obviously, the product $(\text{DE}_{\text{DSi}} \cdot n_s)$ is a real number and have to be approximated to an integer number. Therefore, hereinafter two extreme bounds have been considered to provide a range of values for TRC (minimum and maximum values), as shown in Eq. (7):

$$\bar{n}_i^{\min} = \text{floor}\left(\text{DE}_{\text{DSi}} \cdot n_s \right) \quad \bar{n}_i^{\max} = \text{ceil}\left(\text{DE}_{\text{DSi}} \cdot n_s \right) \quad (7)$$

where the *floor* and *ceil* functions return the nearest integer less than or equal to and the nearest integer greater than or equal to the input real number, respectively. The resulting evaluation of *trc* will be defined below as $\text{trc}_{\min}$ and $\text{trc}_{\max}$ (lower and the upper bounds, respectively). In both cases, it must be verified that:

$$\begin{cases} \bar{n}_3 \leq n_s \\ \bar{n}_i \leq n_s - \sum_{k=i+1}^{3} \bar{n}_k \quad with\, i = 1, 2 \end{cases} \quad (8)$$

to guarantee that: (1) damaged (plan) area always results lower or equal to $(n_s \cdot A)$ due to aforementioned approximations, and (2) if, in a given storey, the contemporaneity of two or

more DSs occurs, the repair activities to be performed are those related to the most severe one only (otherwise the same repairing activities would be wrongly computed more times).

Furthermore, when managing with post-earthquake inspection forms, some information are generally not deterministically known but available within given ranges, i.e., plan area (A) and damage extent DE_{DSi}. Therefore, a Montecarlo simulation is applied to generate 1000 samples different for:

- plan area, A, assumed as uniformly distributed RV within the range provided by the AeDES form for each building (see Fig. 3b);
- and damage extent, DE_{DSi}, assumed as uniformly distributed RV within the ranges:]0; 1/3],]1/3; 2/3],]2/3; 1], for each building.

Finally, to fully compute seismic losses by means of Eq. (6), for each of the 1000 samples obtained from the Montecarlo simulation, a value of C_{DSi}^{IP} and a value of $C_{DSi}^{services}$ are extracted from a lognormal distributions obtained from parameters reported in Tables 5 and 7.

It is worth noting that, based on these assumptions, two different "average damage" $(\overline{DS})$ distributions along the building's height can be associated to each building, related to the minimum or the maximum damage conditions for that building, assuming that $\overline{DS}$ can be expressed as in Eq. (9):

$$\overline{DS} = \sum_{i=0}^{3} (DE_{DSi} \cdot i) = \frac{1}{n_s} \sum_{i=0}^{3} \left(\bar{n}_i \cdot i \right) \tag{9}$$

In Eq. (9), $\bar{n}_i$ is equal to $\bar{n}_i^{min}$ or $\bar{n}_i^{max}$ for the minimum or the maximum damage condition, respectively.

Figure 4 shows 50th, 16th and 84th percentiles (prctile) of such $\overline{DS}$ distribution, obtained for each group of buildings belonging to the dataset characterized by the
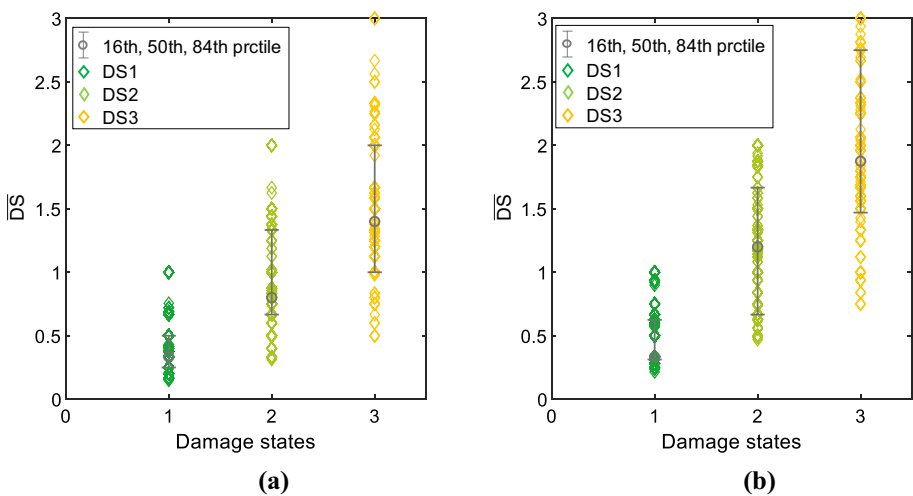
Fig. 4 Average damage level distribution depending on the maximum achieved DS: lower (**a**) and upper (**b**) bound
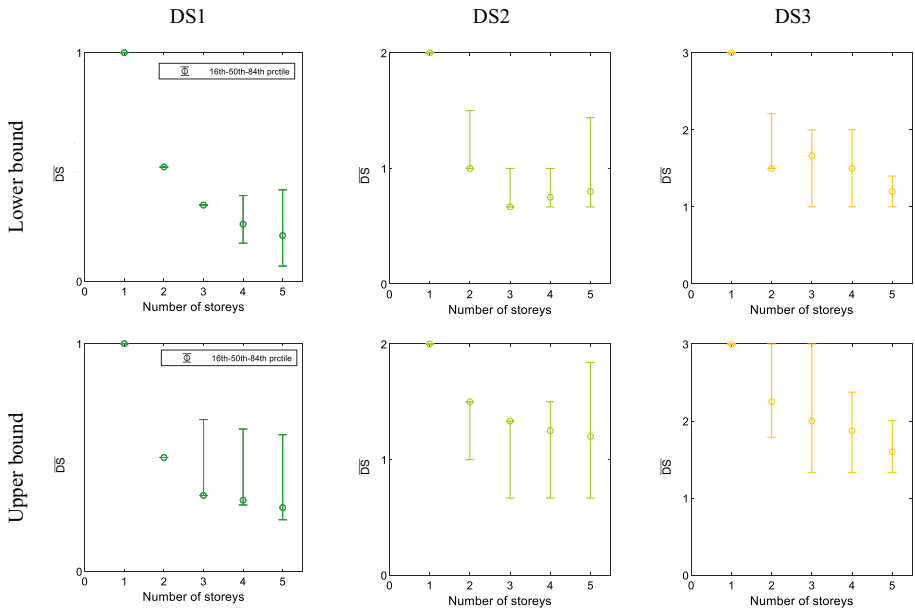
Fig. 5 16th, 50th and 84th of average damage level distribution depending on the number of stories

achievement of the same maximum DS. The minimum and maximum damage conditions are represented in Fig. 4a and Fig. 4b, respectively. It can be noted that, for each building, $\overline{DS}$ is always lower than the corresponding maximum DS achieved in that building.

The average damage level $\overline{\overline{DS}}$ can be also related to the number of stories, n_s, of each building belonging to the dataset, as shown in Fig. 5, where buildings are grouped

Fig. 6 Statistics of predicted *trc* for the investigated building stock depending on the maximum DS: upper and lower bounds for *trc*
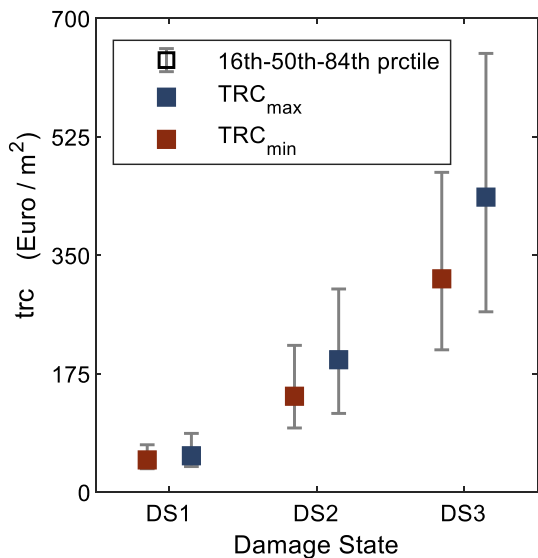
depending on the maximum achieved DS (from DS1 to DS3). Note that n_s has been limited to 5, since buildings with a number of stories bigger than 5 are very rare (see Fig. 3c). Both the lower and the upper damage conditions have been reported. In both cases, at DS1 and DS2, the $\overline{DS}$ tends to decrease when n_s increases from 1 to 3 stories, then keeping a pseudo-constant value (on average) for taller buildings. At DS3, a decreasing trend of $\overline{DS}$ is observed from 1 to 5 stories. Such a decreasing trend can be likely ascribable to a concentration of damage at the lower stories for taller buildings.

5.2.1 Predicted trc

The results of the procedure explained above are reported in Fig. 6, depending on the maximum DS observed after the seismic event. Figure 6 shows 50th (median), 16th, and 84th percentiles (prctile) of the estimated *trc* both in the lower and in the upper bound hypotheses.

It can be noted that, median *trc* value varies from 47.5 to 53.6 €/m^2 when the maximum observed DS is DS1; it ranges between 141.5 and 195.5 €/m^2 at DS2; 315.0 to 435.6 €/m^2 are required at DS3, as median *trc* value. Note that *trc* values shown in Fig. 6 are characterized by a high variability, since they are provided as a function of the maximum observed DS (maxDS) only.

Nevertheless, a lower variability in *trc* prediction can be obtained if co-existing damage and its extent are also considered, namely if *trc* is expressed as a function of the average damage level ($\overline{DS}$) defined above (see Eq. 9). In Fig. 7, *trc* is shown as a function of $\overline{DS}$ for both the lower and the upper *trc* bounds. Separated plots are presented depending on the
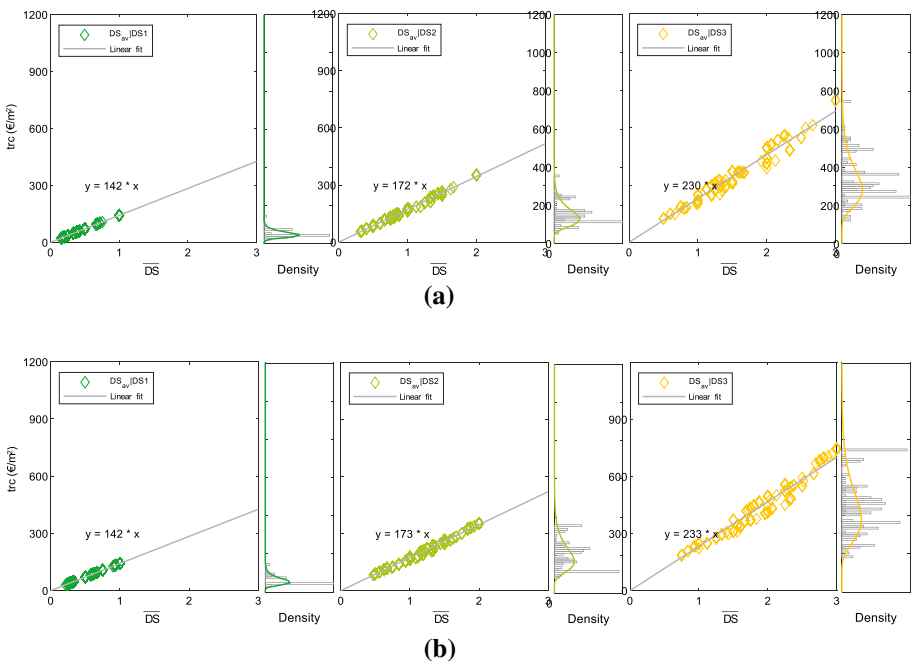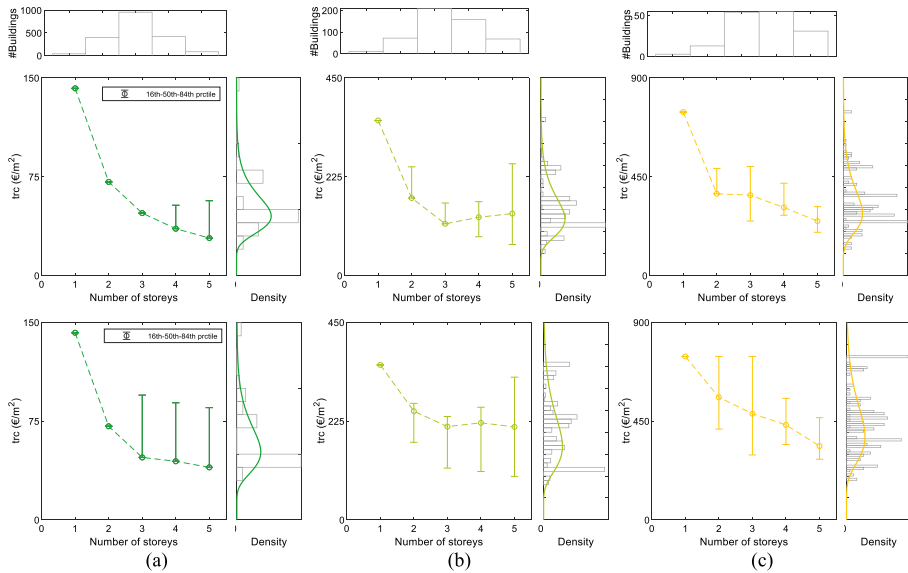

Fig. 7 Lower (**a**) and upper (**b**) bounds of *trc* depending on average damage level ($\overline{DS} = DS_{av}$)

Fig. 8 *trc* depending on the number of storeys when the maximum achieved DS is DS1 (**a**), DS2 (**b**), or DS3 (**c**)—lower (first row) and upper (second raw) bounds. On the top: frequency distribution of buildings' n_s

maximum DS achieved by each of the analyzed buildings, together with the frequency distributions of *trc* interpolated with a log-normal probability density function. First, it can be observed that a clear linear trend exists between the average damage and the estimated *trc*, with an increasing slope for increasing maximum damage severity, as expected. Additionally, *trc* points are very close to such a linear fitting, thus highlighting that *trc* can be better predicted—or better "explained"—by $\overline{DS}$ than by the maximum achieved DS. In other words, if the average damage is known, the *trc* value can be computed with a lower dispersion with respect to prediction based on the maximum achieved DS only. Obviously, when the average damage is exactly equal to a given maximum DS_i (with i = 1, 2, 3), *trc* can be very easily computed as the sum of the repair costs per floor unit related to infills and services (coming from Tables 5 and 7, respectively) at that DS_i. In these specific cases, it can be easily verified that the ratio between *trc* and $\overline{DS}$ ($=DS_i$) is very close to the slope of the linear fittings plotted in Fig. 7.

Given the trend of *trc* with the average damage $\overline{DS}$ (Fig. 7) and the trend of $\overline{DS}$ with the number of stories n_s (Fig. 5), it can be useful to show how *trc* varies with n_s, as in Fig. 8. Note that the number of stories and the maximum achieved DS are information easier to know with respect to the average damage (which also requires the knowledge of the damage extent). Therefore, the prediction of *trc* depending on n_s and maximum achieved DS can be certainly easier to perform. Figure 8 shows that such trend reflects what was already shown and explained in Fig. 5, as expected, due to the almost linear relationship between *trc* and $\overline{DS}$. Therefore, *trc* decreases, on average, when n_s varies from 1 to 3 when the maximum achieved damage is DS1 or DS2, then keeping an almost constant value for higher n_s. At DS3, a decreasing trend of *trc* is observed, on average, for n_s varying from 1 to 5. The clear trend of the *trc* with the number of stories allows to (partially) explain the variability of the *trc* shown in Fig. 6.

Figure 8 also shows that *trc* values for 1-storey buildings are always equal to the sum of unit costs for infills/partitions and services reported in Tables 5 and 7 ($C_{DSi}^{IP} + C_{DSi}^{services} = C_{DSi}$) at the ith DS. This is the consequence of an implicit assumption, i.e., whenever a building resulted damaged according to inspection data, regardless from severity and extension, at least one story must be affected by repairing activities in both the lower and the upper damage bounds, otherwise a zero value of *trc* would be related to a non-zero value of $\overline{DS}$. On the contrary, for taller buildings, a certain degree of damage distribution along the building's height can be observed. Therefore, the repair cost results lower than the totality of the sum between C_{DSi}^{IP} and $C_{DSi}^{services}$. Based on this concept, data reported in Fig. 8 could be equivalently expressed in "dimensionless" form, as shown in Eq. (10):

$$trc = \sum_{i=0}^{3} DE_{DSi} \cdot \left(C_{DSi}^{IP} + C_{DSi}^{services}\right) = \sum_{i=0}^{3} DE_{DSi} \cdot \left(C_{DSi}\right) \tag{10a}$$

$$\frac{trc}{C_{DS1}^{50}} = \frac{1}{C_{DS1}^{50}} \sum_{i=0}^{1} DE_{DSi} \cdot C_{DSi} \tag{10b}$$

$$\frac{trc}{C_{DS2}^{50}} = \frac{1}{C_{DS21}^{50}} \sum_{i=0}^{2} DE_{DSi} \cdot C_{DSi} \tag{10c}$$

$$\frac{trc}{C_{DS3}^{50}} = \frac{1}{C_{DS3}^{50}} \sum_{i=0}^{3} DE_{DSi} \cdot C_{DSi} \tag{10d}$$
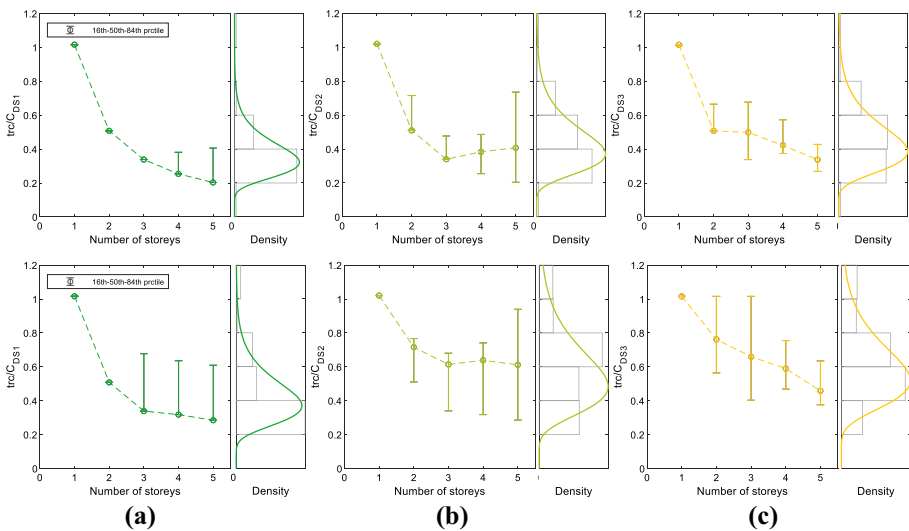
Fig. 9 *trc*-to-C_{DSi}^{50} ratio depending on the number of storeys when the maximum achieved DS is DS1 (**a**), DS2 (**b**), or DS3 (**c**)—lower (first row) and upper (second raw) bounds
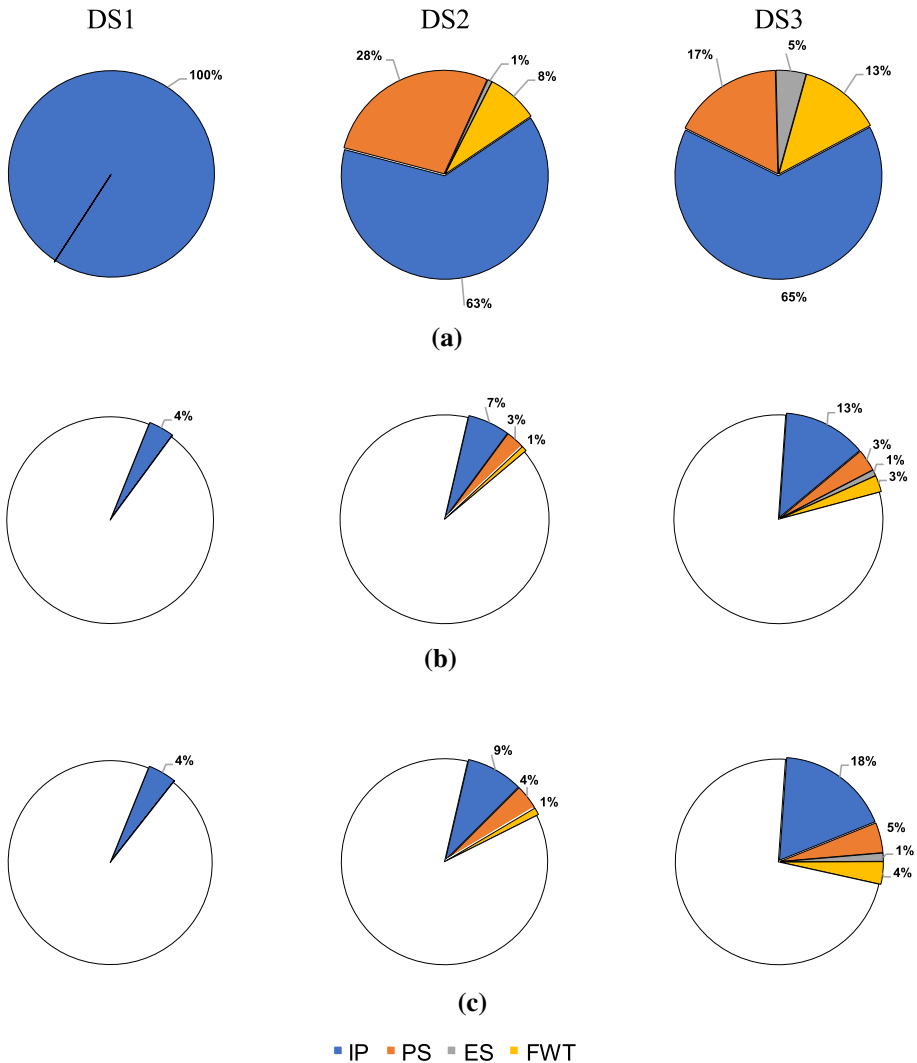
Fig. 10 De-aggregation of the predicted of *trc* depending on the component (IP=infills/partitions; *PS* plumbing system, *ES* electrical system, *FWT* floor/wall tiles): average percentage incidence of each component with respect to the sum of the components (valid for both the lower and the upper bound of the predicted *trc*) (**a**); average percentage incidence of each component with respect to the reconstruction cost of the whole building, for the lower (**b**) and the upper (**c**) bound of the predicted *trc*

where C_{DSi}^{50} (with 1=1, 2, 3) are the median values of C_{DSi}. By applying Eq. (10) to predicted *trc* values, data shown in Fig. 8 can be "converted" in data reported in Fig. 9. In other words, if the maximum DS achieved by a given building and its number of stories are known, predicted *trc* can be assumed as a fraction, lower or equal than the unity, of C_{DSi}, as shown in Fig. 9. The ratios *trc*/C_{DSi} in Fig. 9 can be, thus, regarded as coefficients of damage distribution of each maximum DS_i depending on the number of storeys.

5.2.2 Component-by-component de-aggregation

Additionally, for each maximum DS, the percentage incidence of all the considered cost items can be evaluated, as reported in Fig. 10. More in details, the component "IP" includes all the costs related to repairing activities for infill panels; the item "PS = Plumbing System" includes costs for activities (h) and (i) of Table 6; the component "ES = Electrical System" includes costs for activities (j) of Table 6; "FWT = Floor/Wall Tiles" is related to activities groups (k) and (l), as specified in Sect. 3. All these cost items already include technical costs (as shown in Tables 2 and 6).

In Fig. 10a the same percentage incidences of each cost item ("IP", PS", "ES", "FWT") are observed in both the upper and the lower bound of *trc*, since the cost items are obtained by multiplying their unit costs by the same coefficients (i.e., $\bar{n}_i^{min}$ or $\bar{n}_i^{max}$ shown in Eq. (7) for the lower and upper bound, respectively), thus keeping invariant their proportion with respect to *trc*.

When the maximum damage is DS1, the whole *trc* is due to the repairing activities related to infills/partitions (Component "IP"). Repair costs related to plumbing ("PS"), electrical system ("ES") and floor/wall tiles ("FWT") are null at DS1 because repairing activities related to services are assumed to be not necessary for a very low damage level at infills (Sect. 3).

When the maximum damage level is DS2, repair costs related to infills/partitions and plumbing system are comparable, on average. Only 8% of the estimated *trc* is due to floor/wall tiles replacement. Technically null (1%) is the percentage incidence of repairing activities related to the electrical system.

Lastly, for buildings with maximum damage level DS3, on average, 65% of the estimated *trc* is due to infills and partitions. Note that the incidence of infills/partitions at DS3 also includes costs due to replacement of openings (windows/doors), which represents a not negligible portion of the total repair activities related to infills (about 25%), as found in Del Gaudio et al. (2019b). At DS3, only 5% to the electrical system, and the remaining portion is divided between plumbing system (17%) and floor/wall tiles (13%).

In summary, on average, repair cost due to infills and partitions represents about sixty percent of the whole *trc* at DS2–DS3, namely for medium level of damage, as also found in Del Vecchio et al. (2019).

The average percentage incidence of each component with respect to the total reconstruction cost of the whole building can be also computed as shown in Fig. 10b,c, by assuming that the latter is equal to 1192 €/m² , as suggested by Di Ludovico et al. (2017a) based on actual data related to L'Aquila (Italy) city.

It can be noted that at DS2 the repair costs due to "IP", "PS", "ES", and "FWT" range from 11 to 14% of the reconstruction cost, namely it is in very good agreement with data analysis reported in Di Pasquale et al. (2005) and Cosenza et al. (2018). In particular, the latter study indicated that repair cost is equal to 15% of the reconstruction cost at Damage Limitation Limit State—as defined in Italian (D.M. 2008, 2018) or European (CEN 2004) codes—namely at a "limit state" that can be assumed as coincident with the damage state DS2 investigated in this work (Sassun et al. 2016; Del Gaudio et al. 2019b).

Lastly, the sum of repairing activities required for "IP", "PS", "ES", and "FWT" fall within the ranges [4; 4.5]% and [20; 28]% of the total reconstruction cost, at the DS1 and DS3, respectively, considering the lower and upper bounds of *trc*.
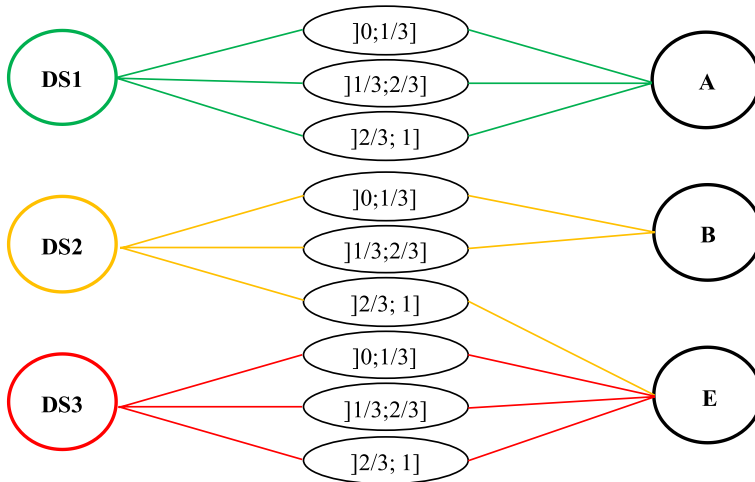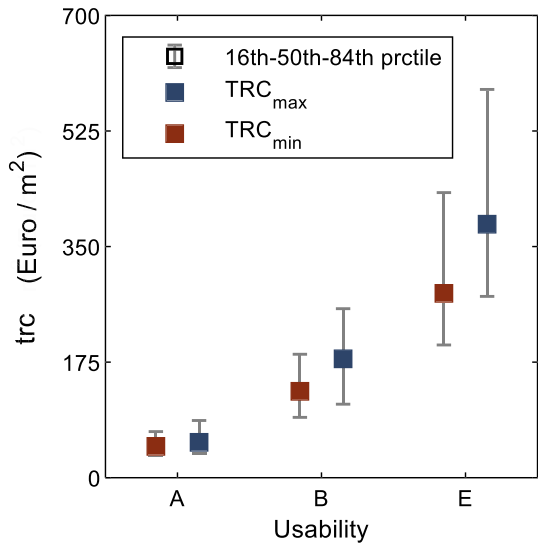
Fig. 11 Conversion from maximum DS and its damage extent to usability rating

Fig. 12 Statistics of predicted *trc* for the investigated building stock depending on the usability rating

5.3 Comparison between *predicted trc* and *actual trc*

Predicted *trc* are finally compared herein with the actual repair costs. First note that predicted repair costs have been obtained until now depending on the maximum DS or on the average damage. On the contrary, the actual *trc* have been provided in the literature (Dolce and Manfredi 2015; Di Ludovico et al. 2017a, b) thanks to an extensive and detailed analysis of the actual design documents realised during L'Aquila reconstruction process, depending on the Usability Rating (UR) of the buildings. Possible URs, ordered from "A" to "F", have been introduced in Sect. 5.1 (more detailed description can be found in Baggio et al.

2007), and they synthetically represented the main parameter to define the reconstruction refund level. Additionally, only URs "A", "B" and "E" are considered herein (as in previous literature, e.g., Dolce and Manfredi 2015; Di Ludovico et al. 2017a, b) since a definitive and rational interpretation of URs "C", "D", or "F" is not trivial when a large subset of data is managed. Therefore, a conversion from observed DS (with its extent) to UR is necessary in order to compare predicted and actual repair cost.

The conversion assumed herein is reported in Fig. 11, based on (1) the DSs description reported in Sect. 2 and (2) Baggio et al. (2007)'s suggestions (which represents the main basis of the AeDES form). As shown in Fig. 11, DS1 corresponds to UR "A" (i.e., usable building); DS2 corresponds to UR "B" (i.e., temporary unusable) if its extent is lower than 2/3 of the whole building; otherwise the resulting UR is "E" (i.e., unusable building). Obviously, UR "A" includes also undamaged buildings (with maximum damage DS0).

Given the assumptions in Fig. 11, predicted *trc* can be finally obtained depending on the UR. Figure 12 shows 50th (median), 16th, and 84th percentiles (prctile) of the estimated *trc* depending on the UR, both in the lower (trc_{min}) and in the upper (trc_{max}) bound hypotheses introduced in the previous section. Note that when the repair costs for "A" buildings must be evaluated, only buildings in DS1 are considered, since buildings in DS0 should be undamaged and thus repairing activities should be not necessary.

As mentioned before, actual *trc* can be obtained in the literature from Dolce and Manfredi (2015).

First, Dolce and Manfredi (2015) provides the mean repair cost for buildings characterised by UR "B". Then, *actual trc* for UR "E" are divided in two categories (according to Dolce and Manfredi 2015): the first one is related to UR "E" mainly due to severe damage to the vertical structures, roofs,…; the second one is a special class of buildings, classified as "E–B", which were characterised by UR "E" mainly due to the damage to infills and partitions. This means that only actual *trc* for buildings with "E–B" should be compared with the predicted *trc*, since the building stock investigated in this section presents no damage to structural components different from infills and partitions.

Dolce and Manfredi (2015) also provide standard deviation values for actual costs (std_{trc}) related to buildings with UR "B" and "E–B". Unfortunately, such values of actual std_{trc} includes the variability of both repair costs and retrofitting costs. Therefore, actual std_{trc} is expected to be higher than standard deviation of actual costs related to repairing activities only, like those predicted in this work.

Actual trc for UR "A" were not known from actual repairing activities required for very slightly damaged buildings. Nevertheless, for buildings resulting in UR "A" that exhibited a very slight damage after L'Aquila 2009 earthquake, Italian government funded the necessary repairing activities with a flat-rate amount of money, at maximum equal to 10,000 € per dwelling (Dolce and Manfredi 2015; OPCM 3778 6/06/2009). Therefore, if the number

Table 11 Predicted versus actual mean values of trc

UR	Mean predicted trc_{min} (€/m²)	Mean predicted trc_{max} (€/m²)	Mean actual trc_{actual} (€/m²)	Mean predicted trc/mean actual trc (–)
A	52.3	62.0	64.0	0.82–0.97
B	140.5	186.3	183.8	0.76–1.01
E–B[a]	311.3	421.6	342.4	0.91–1.23

[a]Classified as "E–B" in Dolce and Manfredi (2015)

Fig. 13 Predicted versus actual *trc*
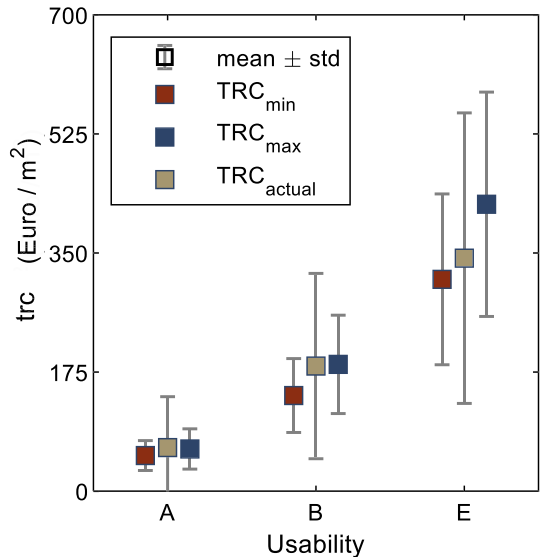
of stories, the average plan area and the number of dwellings per each building resulting in UR "A" (maximum damage DS1) are obtained from Da.D.O. platform data, the actual repair cost (with its std$_{trc}$) can be obtained also for UR "A"-buildings.

In summary, mean values of actual *trc* obtained according to Dolce and Manfredi (2015) for UR "A", "B" and "E–B" are reported in Table 11 and compared with predicted mean *trc* values. It can be noted that predicted and actual mean values of *trc* are quite close to each other. For buildings with UR "A" and "B", actual costs are slight underestimated (− 11%, on average between *trc*$_{min}$ and *trc*$_{max}$). When buildings with UR "E–B" are considered, on average, the percentage relative prediction error is significantly low (equal to + 7%).

Finally, Fig. 13 shows the comparison between actual and predicted costs in terms of mean *trc* ± std$_{trc}$. It can be noted that std$_{trc}$ values related to both the lower and the upper bounds of *trc* describe a wider range of variability of the predicted *trc*, ascribable to the uncertainty in the knowledge of the storey-by-storey extent of repairing activities (as explained in Sect. 5.2). Despite such aspect, the actual variability is higher than the predicted one (also combining together trc$_{min}$ and trc$_{max}$ hypothesis), likely mainly due to the inclusion of the variability related to retrofitting costs, too, in the actual std$_{trc}$ values provided by Dolce and Manfredi (2015).

6 Conclusions and further developments

In this work, a component-based methodology to predict seismic losses for residential RC structures has been proposed, focusing on the contribution of masonry infills/partitions and services. It can be used starting from the expected damage level to infills and partitions, both (1) predicted by means of numerical tools or (2) directly obtained by post-earthquake in situ surveys. Costs for infills and partitions, have been evaluated based on a list of refurbishment activities and depending on the Damage State (DS) of the infill panel only. DSs were defined according to the European Macroseismic scale (Grunthal 1998), from DS1

to DS3 (namely, for DSs involving damage to infills according to EMS-98). Additionally, this work proposes a relationship between repair costs and the so-called "mean damage" (including damage level and extension), given the achieved maximum damage state, which allows significantly reducing the dispersion in loss prediction, along with a trend of repair cost with the number of stories.

Thanks to the post-earthquake in-situ surveys after L'Aquila (Italy) 2009 earthquake, the loss prediction methodology has been first validated by means of the comparison with actual repair costs related to specific case-study buildings. The mean predicted-to-actual total repair costs ratio for these buildings results very close to the unity.

Lastly, a large-scale level validation of the methodology is carried out by analysing a wide dataset of (about 2500) RC buildings, mainly resulting damaged to infills and partitions with very slight or null damage to structural components. Actual repair costs for this building stock were obtained from previous studies from the literature about the topic (Dolce and Manfredi 2015; Di Ludovico et al. 2017a, b). It was observed that the actual costs are well predicted by the presented methodology.

The application of the procedure showed promising results for seismic loss estimation of infilled residential RC buildings typical of the Mediterranean area. However, a further research effort should be addressed towards the integration of the described methodology with repair costs related to structural members for a comprehensive assessment of seismic losses, especially for higher damage level. An additional future extension of the presented procedure will be devoted to considering also the variability of unit costs, which can be different from those adopted herein, depending, for example, on the geographic area or on the market laws.

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