Relationships between empirical damage and direct/indirect costs for the assessment of seismic loss scenarios

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Received: 8 June 2021 / Accepted: 15 September 2021 / Published online: 5 October 2021
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Abstract

The definition of relationships between damage and losses is a crucial aspect for the prediction of seismic effects and the development of reliable models to define risk maps, loss scenarios and mitigation strategies. The paper focuses on the analysis of post-earthquake empirical data to define relationships between buildings' damage expressed as usability rating or as global damage state and the associated costs for repair (i.e. direct costs) or for population assistance (i.e. a part of total indirect costs). The analysis refers to the data collected on residential buildings damaged by 2009 L'Aquila earthquake. For different usability rating or damage states, the paper presents the costs expressed in terms of percentage with respect to the reference unit cost of a new building ($\%C_r$ and $\%C_a$ for repair and population assistance costs, respectively). In particular, the costs analysis refers to undamaged, lightly or severely damaged buildings classified according to usability rating (i.e. A, B-C or E according to Italian classification) or to five different global Damage States (DSs). DSs comply with European Macroseismic Scale (EMS-98) and derive from literature available matrices properly defined to convert empirical damage to structural and non-structural components into building global damage. The $\%C_r$ probability density functions and relevant statistics derive from the analysis of actual data of post-earthquake reconstruction process, while, to determine those related to $\%C_a$, a deep analysis of population assistance types, person/month assistance cost for each assistance form, and a methodology to associate such costs to each building are herein presented and discussed. Finally, the paper presents a relationship calibrated on empirical data to directly correlate repair costs on a building with assistance costs to their occupants. The relationships between empirical damage and direct and indirect costs herein presented are of paramount importance because they allow reliable loss scenarios to be defined by simply using literature fragility curves (defined according to empirical or mechanical approaches) aimed at evaluating the probability of exceeding different usability rating or damage states of existing buildings.

Keywords Repair costs · Population assistance costs · Direct and indirect costs · Empirical damage · Usability rating · Damage states · Post-earthquake reconstruction process · Loss scenarios

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1 Introduction

The assessment of seismic risk maps at a national scale is a crucial tool for investigating potential losses due to earthquakes in a region and for programming and introducing appropriate mitigation policies. In last 20 years, there has been a worldwide growing interest in developing seismic maps (RISK-UE 2001–2004; Zuccaro 2004; Lagomarsino and Giovinazzi 2006; Pitilakis et al. 2006; Shakib et al. 2011; Silva et al. 2015; Chaulagain et al. 2015; NDCP ed., 2018; Silva et al. 2019; Dolce et al. 2020). To this aim, the combination of data coming from seismic hazard, structural vulnerability and exposure is needed; in particular, the definition of building vulnerability classes and relevant fragility curves to derive potential damage levels at a given earthquake intensity is crucial to assess reliable prediction of losses. Several seismic intensity measures have been used in recent years for characterization of seismic hazard: macro-seismic intensity scales; Peak Ground motion Acceleration, PGA, Velocity (PGV), Displacement (PGD), or spectral acceleration (Spence et al. 1992; Musson 2000; Rossetto 2014). Fragility curves may be determined by means of different approaches, based on the observed data occurred in past seismic events (i.e. empirical approach, Braga et al. 1982, Rossetto and Elnasjaj 2003; Rota et al. 2008, Zuccaro and Cacace 2015, Del Gaudio et al. 2017; Rosti et al. 2018; Del Gaudio et al. 2019a; Del Gaudio et al. 2020; Rosti et al. 2020; da Porto et al. 2021) or on the assessment of damage predicted by buildings' modelling (i.e. analytical approach, Rossetto and Elnashai 2005; Lagomarsino and Giovinazzi 2006; Borzi et al. 2008; Rota et al. 2010).

Then, the assessment of risk is not only affected by uncertainties related to fragility curves, but it is strongly correlated to the definition of suitable damage thresholds (empirically or mechanically based) and their correlation with losses.

The correlation in terms of direct and indirect economic losses is a challenging task (Guha-Sapir and Santos 2013), especially for what concern indirect losses that are not straightforwardly expressed in monetary terms but can significantly impact on the Gross Local Product (GLP).

The current efforts of the scientific community aim at integrating risk maps with data related to economic losses intended as the sum of the direct costs necessary to repair the damage detected on buildings following a seismic event, and the associated indirect costs (e.g. IRMA (Italian Risk Maps) Borzi et al. 2021, and CAESAR II tool, Zuccaro et al. 2021). The former may derive from the analysis of the most recent cost data for the reconstruction of areas affected by the earthquake. As far as indirect costs are concerned, the assistance costs to the population certainly represents a significant ratio of losses (Mannella et al. 2017) in addition to those due to the interruption of economic activity and the reduction of production in the industrial sector (Benson and Clay 2004).

The present study aims at investigating direct and indirect costs by analysing data related to the reconstruction process of reinforced concrete (RC) and masonry residential buildings damaged by L'Aquila 2009 earthquake (Di Ludovico et al. 2017a). In particular, the direct costs are analysed as a function of different parameters representative of the building damage: usability rating (i.e. usable, unusable with light damage, unusable with severe damage); reconstruction class (i.e. light reconstruction and heavy reconstruction); and global damage state (DS) defined through different conversion matrices on the basis of empirical damage observed on structural and non-structural components. Indirect costs in the form of assistance population costs are also associated to buildings by analysing the costs related to financial assistance for accommodation in tents, hotels, self-accommodations (so-called "self-accommodation grant, s.a.g.") or structures intended to outlast the recovery

timeframe (i.e. M.A.P., Temporary Inhabitable Modules, or the so-called “C.A.S.E. project”, Anti-seismic, Sustainable and Ecologically Compatible Housing Complexes). The costs of each assistance form are computed for each person, associated to buildings’ occupants, and analysed for different levels of buildings’ empirical damage.

The usability assessment aims at evaluating the safety conditions of the buildings and the actions required to enable people to return to their houses. The data herein analysed refers to usability assessment of buildings according to Italian classification based on the AeDES survey form (Baggio et. al. 2007). However, the study can be easily extended to other seismic prone countries, which commonly adopt similar forms aimed at the final evaluation of usability categories (e.g. Japan, Goretti and Inukai 2002; U.S., ATC, 2005; New Zealand, NZSEE, 2009). For example, according to ATC, 2005, a building is tagged “Green” for unrestricted access, “Yellow”, for restricted access, and “Red” for no access, while the AeDES form leads to six usability categories: A. Usable buildings; B. Building usable only after short term countermeasures; C. Partially usable building; D. Building to be re-inspected; E. Unusable building; F. Unusable building for external risk.

The correlation between usability rating and costs is particularly valuable to quickly predict losses in the immediate post-earthquake because the usability rating of buildings is generally evaluated in the initial emergency stages. It also provides the opportunity to predict the ratio of indirect losses related to population assistance; indeed, population assistance costs are strictly correlated to the housing recovery time that mostly depends on usability rating. Thus, relationships between usability rating and direct and indirect costs are crucial to those involved in the post-emergency reconstruction phases management because they may give the opportunity to plan an overall economic development plan. However, the risk assessment in “peace time”, starting from models based on the usability rating and relevant reconstruction phases prediction is not easily feasible because reliable models to predict the usability rating of buildings are still lacking.

Thus, the costs data associated to building global damage levels are certainly more appropriate for the definition of loss scenarios in “peace-time”. In such a case, once a seismic input scenario is assumed in a given area, with known exposure data, the number of buildings attaining different DSs can be evaluated based on the use of empirical or mechanically based fragility curves; then, the losses can be immediately assessed if association between DS and costs are available. This is a critical issue because significant uncertainties are related to the capability of DSs to consider not only the damage level but also its extent and diffusion, as well as its incidence on repair costs actions (De Martino et al. 2017; Del Vecchio et al. 2018, 2020). Different conversion matrices from empirical damage detected on RC and masonry buildings to building DSs are herein investigated along with the dispersion in terms of predicted costs (both in terms of repair costs and assistance to population costs). Although affected by uncertainties, these data may be essential to define loss scenarios and consequently to drive decisions makers involved in the definition and planning of suitable seismic risk mitigation policies (Cosenza et. al. 2018).

2 Database for the analysis: L’Aquila 2009 post earthquake

The reconstruction process following L’Aquila 2009 earthquake allowed collecting data on 5775 residential damaged buildings outside historical centres: 49% reinforced concrete buildings, 46% masonry buildings, and 5% other types such as mixed, steel etc. (Di Ludovico et al. 2017a).

The present study focuses on a significantly enlarged database made of 8497 residential buildings, which comprises also data on usable buildings outside historical centres (i.e. A rating according to AeDES form), see Table 1. In particular, it refers to 4995 usable buildings and 3502 unusable ones (out of the 5775 analysed in Di Ludovico et al. 2017a). This because on 4995 usable buildings (2421 RC and 2574 masonry buildings) and 3502 unusable ones (2243 RC and 1259 masonry buildings) it was possible to derive all the information needed for the study: damage on structural and non-structural components; repair intervention costs computed by practitioners engaged by property owners to apply for public grant for reconstruction, as regulated by OPCM no. 3778 (2009), OPCM no. 3779 (2009), OPCM no. 3790 (2009), and OPCM no. 3881 (2010) (namely “direct” costs in the following); buildings’ recovery time and costs for occupants’ assistance (namely “indirect” costs in the following, even if they represents only a part of total indirect costs).

The data on building types and damage resulted from the usability assessment surveys carried out in the immediate post-earthquake by using the AeDES form (Baggio et al. 2007). They refer to different usability rating: A rating, 4995 undamaged buildings corresponding to 59% of the database; B or C ratings (B-C in the following), 2180 lightly damaged buildings corresponding to 25% of the database; E rating, 1322 severely damaged building corresponding to 16% of the database, see Table 1.

For the post-earthquake reconstruction, fully coverage of repair costs was guaranteed by the Italian government with a fixed upper bound per dwelling and per common areas of condominiums in case of A rating (Dolce and Manfredi 2015); economic convenience limits were foreseen in case of B-C or E rating buildings (see (Di Ludovico et al. 2017b)). The reconstruction process of B-C buildings (“light damage” reconstruction) started before that related to E ones (“heavy damage” reconstruction) to enable rapid re-occupancy of slightly damaged buildings, thus reducing public costs incurred for homeless housing assistance. Moreover, in the reconstruction process, E-rating buildings were further classified in sub-classes: class E-B, including buildings with a high non-structural damage but with slight structural damage; E_{class} including buildings with severe structural damage, and E_{dem}, including buildings that needed to be demolished. In the E-B class of buildings, a faster local strengthening strategy was mostly selected to overcome the structural

Table 1 Database

Usability rating	Reconstruction class	Building type	No. of buildings
A	A	RC	2,421
		Masonry	2,574
		Total	4,995
B-C	B-C	RC	1,402
		Masonry	778
		Total	2,180
E	E-B	RC	183
		Masonry	30
		Total	213
	E _{class}	RC	420
		Masonry	277
		Total	697
	E _{dem}	RC	238
		Masonry	174
		Total	412

weaknesses. By contrast, in the class E_{dem} demolition was selected as the most viable solution because of strong structural weaknesses, a high residual drift, local or global collapse, or excessive costs of repair/retrofit interventions compared to the costs of demolition and reconstruction (Di Ludovico et al. 2017b). Table 1 summarizes the number of buildings, RC or masonry ones, in each class.

Starting from such buildings' database, a further classification is herein assumed based on the empirical damage detected in the “Sect. 4—Damage to the structural components” of the AeDES form. This section identifies four damage grades (D0-no damage, D1, slight damage; D2-D3 medium-severe damage; D4-D5 very heavy damage or collapse) and relevant extent for structural and non-structural members (i.e. Vertical Structures, VS, Floors, *F*, Stairs, *S*, Roofs, *R*, and Infills-Partitions, *IP*). The empirical damage data have been elaborated in order to derive, for each building, a global Damage State, DS, according to the European Macroseismic Scale EMS-98 (Grunthal 1998). The conversion matrix reported in Del Gaudio et al. (2020) is used to define DS of RC buildings, while that one reported in Dolce et al. (2019) is used for masonry buildings; the former takes into accounts the maximum severity of the damage detected on VS and IP to derive DS, while the latter only refers to damage to VS in terms of both severity and relevant extent.

Figure 1 shows the distributions of the number of RC (a) and masonry (b) buildings as a function of DS for the buildings' database. A peak of 1835 buildings in DS1 and 2151 in DS0 is observed for RC and masonry buildings, respectively.

Tables 2 and 3 summarize the DS distributions as a function of usability ratings and reconstruction classes of RC and masonry buildings, respectively. As expected, the data shows that the higher the DS, the lower is the percentage ratio of A and B-C buildings.

The number of A rating buildings is null for DS greater than DS2: DS0 is the most populated group, 49% and 76% for RC and masonry buildings, respectively. Because damage to *IP* is taken into account in the conversion matrix of RC buildings, DS1 is also significantly populated, 48%.

Fig. 1 Number of buildings for each DS defined according to Del Gaudio et al. (2020) for RC buildings (a) and to Dolce et al. 2019 for masonry buildings (b)

Table 2 The DS distribution as a function of usability ratings and reconstruction classes: RC buildings

Damage states	Usability rating			Reconstruction classes		
	A	B-C	E	E-B	E _{class}	E _{dem}
DS0	49%	7%	0%	0%	0%	0%
DS1	48%	45%	3%	3%	2%	5%
DS2	2%	36%	15%	26%	14%	9%
DS3	0%	12%	56%	60%	62%	42%
DS4	0%	0%	23%	11%	20%	38%
DS5	0%	0%	2%	0%	2%	5%

Table 3 The DS distribution as a function of usability ratings and reconstruction classes: masonry buildings

Damage states	Usability rating			Reconstruction classes		
	A	B-C	E	E-B	E	E _{dem}
DS0	76%	23%	2%	7%	3%	0%
DS1	23%	42%	4%	13%	6%	0%
DS2	1%	26%	12%	20%	14%	7%
DS3	0%	9%	46%	47%	51%	40%
DS4	0%	0%	19%	13%	16%	24%
DS5	0%	0%	17%	0%	11%	29%

The B-C rating buildings mostly belong to DS1 or DS2 (i.e. 45% and 36% for RC buildings, and 42% and 26% for masonry ones). In case of E rating buildings, DS3 is the most populated class: 56% for RC buildings, and 46% for masonry buildings.

Reconstruction class E_{dem} should be analysed to derive peak values of DS4 and DS5; in particular, the peak percentage of DS4, 38%, refers to RC buildings, and the peak percentage of DS5, 29%, refers to masonry buildings. The data reported in Tables 2 and 3 could be very useful to define simple correlations between a single parameter defining the building global damage, that is DS, to a rating defining the usability of buildings in the earthquakes aftermath.

3 Repair costs

The section focuses on the analysis of actual repair costs (i.e. direct costs) related to buildings with different level of damage expressed in terms of: (i) usability rating, A, B-C, E (and relevant reconstruction classes, E-B, E_{class}, E_{dem}); (ii) or global damage, DS.

The actual repair costs have been computed by practitioners involved in the post L'Aquila earthquake reconstruction process; they represent the costs to restore the original conditions of structural or non-structural elements of buildings damaged by the earthquake. They are inclusive of charges for the design and technical assistance of practitioners while they are not inclusive of VAT. The actual costs herein analysed are normalized by the overall building gross surface area (i.e. €/m²); furthermore, in the following, they are expressed as a percentage cost, %C_r, with respect to reference unit cost of a building (i.e. CU, assumed equal to 1.350 €/m² including technical expenses and VAT, NDCP, ed., 2018).

Table 4 $\%C_r$ as a function of usability rating

Usability rating	RC buildings			Masonry buildings		
	A	B-C	E	A	B-C	E
No. of buildings	2,421	1,402	841	2,574	778	481
$\%C_r$ - 16th percentile	0%	6%	24%	0%	7%	23%
$\%C_r$ - median	0%	12%	43%	0%	14%	42%
$\%C_r$ - 84th percentile	4%	22%	87%	5%	25%	86%
$\%C_r$ mean	2%	14%	51%	2%	16%	52%
$\%C_r$ standard deviation	3%	9%	29%	4%	10%	30%
$\%C_r$ CoV	158%	64%	56%	182%	62%	58%

Table 5 $\%C_r$ as a function of reconstruction class

Reconstruction class	841 RC buildings			481 Masonry buildings		
	E-B	E _{class}	E _{dem}	E-B	E _{class}	E _{dem}
No. of buildings	183	420	238	277	30	174
$\%C_r$ - 16th percentile	14%	25%	78%	9%	21%	71%
$\%C_r$ - median	26%	39%	88%	19%	33%	84%
$\%C_r$ - 84th percentile	36%	53%	103%	29%	47%	102%
$\%C_r$ - mean	26%	39%	90%	20%	34%	87%
$\%C_r$ - standard deviation	11%	14%	15%	10%	13%	17%
$\%C_r$ - CoV	42%	35%	17%	50%	37%	19%

3.1 Usability rating

Table 4 summarizes the percentage costs of repair, $\%C_r$, computed for A, B-C and E usability rating buildings; the median, 16th, 84th percentile, mean, standard deviation and CoV are also reported.

Note that the repair costs are also associated to usable buildings (i.e. A rating) for which public coverage of the limited damage was allowed according to OPCM no. 3778 (2009). In particular, OPCM no. 3778 (2009) established a maximum public grant for repair in case of A rating buildings equal to 10.000 € for each condominium unit or independent dwelling and a further contribution up to 2500 € for repair of common areas. For B-C and E rating buildings, no upper bound was defined for repair costs unless repair plus strengthening costs resulted greater than CU (i.e. economic convenience), OPCM no. 3790 (2009). The economic convenience limit was achieved only in case of E rating buildings (i.e. E_{dem} reconstruction class); in such a case the cost for reconstruction has been computed according to provision issued by the Resolution Regional Council DGR no. 615 form (2010) and resulted on average equal to about 1200 €/m². Table 4 shows that mean [median] values of $\%C_r$ resulted: 2% [0%], 14% [12%] and 51%[43%] for A, B-C and E rating RC buildings, and 2% [0%], 16% [14%] and 52% [42%] for A, B-C and E rating masonry ones. The percentage costs of repair, $\%C_r$, related to E rating buildings are explored for different reconstruction classes (E-B, E_{class} and E_{dem}) in Table 5. It resulted that mean [median] $\%C_r$ decreases up to 26% [26%] and 20% [19%] for RC and masonry E-B buildings while it attains 90% [88%] and 87% [84%] for E_{dem} reconstruction class (with 84th percentile greater than 100% in each case). Demolition and reconstruction resulted the most viable solution on about one third of E rating buildings. The mean $\%C_r$ for E-B RC buildings exceeds that one of masonry ones due the significant contribution of infills and partitions; indeed, in RC buildings, they are largely damaged, and this imply significant repair actions and relevant costs. For the same reason, the coefficient of variations, CoV, of buildings

with severe structural damage (i.e. E rating), were generally lower than the ones of buildings with light damage (i.e. B-C rating), see Table 4. This because the high variability of costs related to actions aimed at restoring damage on partitions and curtain walls, and in general on non-structural components (i.e. systems, fixtures, finishes, etc.).

The data reported in Table 4 (and Table 5) are crucial to quickly define loss scenarios in the post-earthquake phases once the usability rating of buildings in the struck area has been completed. However, in terms of predictions these data can be suitably adopted only if fragility curves, able to predict the probability of buildings exceeding given usability rating for a certain seismic intensity, are provided. These curves are generally lacking (Zucconi et al. 2018) because literature studies have been commonly focused on fragility curves expressed as a function of a parameter related to the building global damage, DS (NDCP ed., 2018; Dolce et al. 2020). Although preliminary correlations between DS and usability rating are herein provided based on empirical data recorded in the post L'Aquila 2009 earthquake, to overcome such issue, a direct correlation between repair costs and DS is reported and discussed in detail in the following section.

3.2 Damage state

Table 6 summarizes the percentage costs of repair, $\%C_r$, computed for different damage states, DS; the median, 16th, 84th percentile, mean, standard deviation and CoV are also reported.

Figure 2 shows the frequency distributions and the best fitting probability density function (PDF) of $\%C_r$ for RC (Fig. 2a, c, e, g, i, m) and masonry buildings (Fig. 2b, d, f, h, l, n), respectively; the cumulative distribution function (CDF) of $\%C_r$ is also reported in each graph.

For DS1 and DS2 a mixture distribution has been assumed in order to combine a discrete (degenerate distribution) and a continuous probability distribution (lognormal distribution); indeed, in such DSs a fixed probability value should be assigned to $\%C_r=0$ (e.g. 31% and 35% for RC and masonry buildings at DS1 and 4% for both buildings types at DS2) while for $\%C_r$ greater than 0, a lognormal distribution approximates well the distribution of $\%C_r$. For DS3 and DS4 a mixture distribution of two lognormal distributions has been assumed in order to capture the trend of data that are affected by two different probability peaks. Indeed, severely damaged buildings mostly belongs to such DSs and, thus, if demolition resulted the most convenient solution, the $\%C_r$ values shifted to higher $\%C_r$ values with respect to $\%C_r$ related to repairable buildings. Finally for DS5 a normal distribution has been assumed for RC buildings to obtain the best fitting probability density function while a mixture of a normal and a lognormal distribution has been assumed for

Table 6 $\%C_r$ as a function of damage states, DS.

	4,664 RC buildings					3,833 RC buildings				
Damage States	DS1	DS2	DS3	DS4	DS5	DS1	DS2	DS3	DS4	DS5
No. of buildings	1,835	690	643	194	20	941	276	292	92	81
$\%C_r$ - 16 th percentile	0%	6%	14%	26%	44%	0%	8%	16%	25%	34%
$\%C_r$ - median	3%	14%	34%	59%	81%	4%	17%	33%	52%	72%
$\%C_r$ - 84 th percentile	13%	29%	64%	95%	107%	17%	35%	78%	96%	95%
$\%C_r$ - mean	6%	19%	39%	62%	78%	8%	22%	41%	59%	67%
$\%C_r$ - standard deviation	10%	18%	26%	32%	32%	10%	19%	28%	33%	29%
$\%C_r$ - CoV	64%	105%	149%	195%	191%	76%	116%	157%	163%	235%

masonry buildings. Figure 2a–f also reports the PDF key parameters such as degenerate distribution x and y coordinates, the proportion parameter P_p in a mixture of distributions, the median and scatter of lognormal distribution, e^μ and e^σ , as well as mean and standard deviation of normal distribution, μ and σ .

4 Population assistance costs

The section focuses on the analysis of population assistance costs. They are a significant part of indirect costs in the post-earthquake recovery process. In the first emergency phase of 2009 L'Aquila earthquake, two different types of assistance to the population were provided: accommodation in tent camps set up by the Department of Civil Protection (DPC) and hospitality in hotels, mainly located on the Adriatic coast (about 70 km away from L'Aquila). In particular, 35690 people were assisted in 5957 tents of 171 camps and 33964 people in hotels (Dolce 2010a; Mannella et al. 2017), for a total of 69654 people.

The huge number of displaced people highlighted the need to adopt several types of assistance to the population who lived in light or heavy damaged buildings: hotels; self-accommodation grant (namely s.a.g. in the following), traditional temporary wooden-house units, M.A.P. ("Temporary Inhabitable Modules"), and innovative high quality and comfort standards housing modules, so-called C.A.S.E. project ("Anti-seismic, Sustainable and Ecologically Compatible Housing Complexes"), (Dolce 2010a). In the framework of the C.A.S.E. project 4500 apartments located in 185 buildings were built with the capacity to accommodate a maximum of 15000 people (DPC 2018b). Temporary units, M.A.P., consisted of 3166 wooden housing modules, out of which 1113 for the districts of L'Aquila able to accommodate a maximum of 3324 people (DPC 2018), and 2053 in the other municipalities. The construction of M.A.P modules and C.A.S.E. project started on June 2009 and ended in February 2010. The first apartments were delivered on September 2009.

The types of assistance have been used in a complementary and flexible manner taking into account the progress of demand (i.e. number of people needing assistance) and capacity (available housing accommodation in the temporary facilities, i.e. M.A.P. and C.A.S.E.). The usability rating of buildings also played a crucial role in the population assistance evolution because people living in severely damaged buildings were mainly hosted in M.A.P. and C.A.S.E.

In order to provide actual data on population assistance costs, a proper database has been developed in this study. It collects data on the number of assisted people for each month and each type of assistance and relevant costs; they derive from reports published by Deputy Commissioner for Reconstruction, Department of Civil Protection and the Special Offices for the Reconstruction of historical centres of L'Aquila (USRA, <https://usra.it/>) and the other municipalities (USRC, <http://www.usrc.it/>).

Figure 3 shows the number of assisted people per month for each type of assistance (i.e. tents, hotels, s.a.g., M.A.P., C.A.S.E.); the actual data refers to the period April 2009–December 2018 but the graphs also reports the trends up to December 2024 which is the supposed end of the reconstruction process according to USRA and USRC source of data (month 1–189 in the graph). Indeed, according to the current trend of people returning home they suppose that the assistance to people will end in 2024, with a total duration of 15 years and half (189 months). Thus, a linear decreasing trend of assisted people per month has been assumed in Fig. 3d, e in the period from December 2018 up to December 2024 (see dot black line).

Fig. 2 Frequency distribution of $\%C_r$ related to RC (a,c,e,,g,i,m) and masonry (b,d,f,h,l,n) buildings at different damage states, *DS*

Figure 3 shows that, in the months immediately following the event, tents, hospitality in hotels and self-accommodation grant, s.a.g., were widely used as assistance types. Then a significant portion of people started to be assisted in M.A.P. and C.A.S.E. Assistance in tents, hotels and s.a.g. fully ended after 8, 45, and 71 months, respectively (Fig. 3a, b, c). After 108 months, 8024 and 2149 people were assisted in C.A.S.E and M.A.P. (Fig. 3d, e).

The data related to number of assisted people per month allowed the costs associated to tents, hotels and s.a.g. to be directly calculated. The overall costs resulted to be about: 175 million euros for hospitality in tents (note that the cost of tent disposal is not taken into account while the costs include: supply of goods and services, extraordinary expenses for first assistance, supply of meals, foodstuffs, waste management, sanitation and cleaning, transport and temporary storage of furniture); 319 million Euros for hospitality in hotels;

Fig. 2 (continued)

and 235 million Euros for the self-accommodation grant (s.a.g.). For these types of assistance, the costs are strictly correlated to the duration of the assistance and the public cost is sustained continuously over time. The ratio between the overall costs of the hospitality type and the sum of assisted people per month allowed to determine the average cost per month per person, C_p , for tents, hotels and s.a.g. accommodation types equal to €1191.20; €1524.40; and €227.40 respectively. Table 7 summarizes for each assistance type the data related to the number of months of assistance and relevant mean number of people assisted per month in the period of assistance as well as the mean cost per month per person.

In case of C.A.S.E and M.A.P. assistance types, the initial costs for the construction of new facilities should be taken into account to define normalized costs per month per person. The construction of 1113 M.A.P. amounted to about 116 million euros while that of C.A.S.E. project amounted to about 853 million euros for the construction of 185 buildings including 4449 apartments (<http://www.protezionecivile.gov.it>).

Fig. 2 (continued)

To define the assistance duration in M.A.P. and C.A.S.E assistance types, it has been assumed the end of the reconstruction in December 2024 (i.e. 189 months after the earthquake and 182 and 184 months after the beginning of assistance in M.A.P. and C.A.S.E., respectively, see Table 7); thus, according to graphs of Fig. 3d, e it is possible to estimate a mean assistance cost per person per month of € 581.70 and € 350.20 for C.A.S.E and MAP respectively. Note that such costs are not accounting for the residual economic value of the C.A.S.E. project buildings and for the possible revenue from potential alternative uses of the empty apartments before 2024.

4.1 A methodology to normalize people assistance costs to building reconstruction cost

This section aims at defining a procedure to correlate the population assistance costs to each building as a function of its damage level expressed in terms of usability rating or damage state. In particular, the goal is to express the assistance costs in terms of percentage cost with respect to the reference unit cost of a new building, namely $\%C_a$ in the following.

To pursue such objective, a first step of the proposed procedure is the definition of a weighted population assistance cost per month, $C_{a,j}$, computed as:

$$C_{a,j} = \sum_i \% \gamma_{ij} \cdot C_i \quad (1)$$

where $\% \gamma_{ij}$ is the percentage of assisted people in the i th assistance type (tents, hotels, s.a.g., C.A.S.E. and M.A.P.) in the j th month; and C_i is the mean cost per person per month in the i th assistance type. The distribution of $\% \gamma_{ij}$ and the relevant $C_{a,j}$ expressed as €/month/person for each month in the period April 2009– December 2024 is depicted in Fig. 4.

Fig. 3 Number of assisted people per month in tents (a), hotels (b), self-accommodation grant s.a.g. (c) C.A.S.E project (d) and M.A.P. (e)

Table 7 Cost per person per month for different assistance types

Assistance form	No. of months of assistance	Mean no. of people assisted / month	Mean Cost/ month/person, C_i
Tents	8	18335	€1,191.2
Hotels	45	4650	€1,524.40
s.a.g	72	14325	€227.40
C.A.S.E. project	184	7969	€ 581.70
M.A.P	182	1823	€ 350.20

Once $C_{a,j}$ is computed, it is possible to compute $\%C_a$ for each building according to the following expression:

$$\%C_a = \frac{\sum_{j=1}^t C_{a,j} \cdot n_{occ}}{CU \cdot S_L} \quad (2)$$

where t is the period of repair and strengthening building site works; n_{occ} is the number of building occupants derived from AeDES form; CU is the reference unit cost of a new building assumed equal to €1,350/m²; and S_L is the overall building gross surface area. Note that expression (2) assumes that the people living in a building have been assisted according to the distribution $\% \gamma_{i,j}$ in the assistance period.

According to expressions (1) and (2), it was possible to assess the $\%C_a$ as a function of usability ratings, reconstruction classes or damage states of buildings; in particular, $\%C_a$ has been computed on a subset of 7,847 buildings out of 8,497 buildings due to the lack of information on number of occupants of 650 buildings.

4.2 Usability rating

The $\%C_a$ has been evaluated for 2,852 out of 3,502 unusable (i.e. B-C and E rating buildings) buildings (see section §2) due to the lack of information on number of occupants

Fig. 4 Distribution $\% \gamma_{i,j}$ (a) and $C_{a,j}$ (b) in the reconstruction process period

Fig. 5 $\%C_a$ frequency distribution for RC (a, c) and masonry (b, d) buildings as a function of usability rating

on 650 buildings: 1,827 B-C rating buildings (1,216 RC and 611 masonry buildings) and 1,025 E rating buildings (692 RC and 333 masonry buildings). The $\%C_a$ for usable buildings (i.e. A rating buildings) is zero because no assistance is provided in this case. Figure 5 shows the frequency distributions and the best fitting probability density function (PDF;

Table 8 $\%C_a$, statistical parameters as a function of usability rating

	1,908 RC buildings		944 Masonry buildings	
Usability rating	B-C	E	B-C	E
No. of buildings	1216	692	611	333
$\%C_a$ - 16 th percentile	5%	10%	5%	9%
$\%C_a$ - median	10%	23%	11%	18%
$\%C_a$ - 84 th percentile	21%	41%	24%	35%
$\%C_a$ mean	13%	26%	15%	22%
$\%C_a$ standard deviation	11%	16%	13%	16%
$\%C_a$ - CoV	119%	161%	115%	139%

log-normal) of $\%C_a$ for RC (Fig. 5a, c) and masonry buildings (Fig. 5b, d). The cumulative distribution function (CDF) of $\%C_a$ is also reported in each graph. Figure 5 shows that the log-normal function well approximates $\%C_a$ distributions.

Table 8 summarizes the number of buildings and the median 16th and 84th percentile of $\%C_a$ computed for B-C and E usability rating buildings. The data show that the impact of population assistance on the amount of costs sustained after the earthquake is really significant and it can also be comparable to that related to repair costs. In particular, mean [median] $\%C_a$ resulted on average comparable to mean [median] $\%C_r$ for lightly damaged buildings (i.e. B-C rating), see Table 4. This is because the population assistance of people living in lightly damaged buildings, even if it is not a long term assistance, mainly involves very expensive assistance types, that is the first emergency ones (i.e. tents and hotels). In case of severely damaged buildings mean [median] $\%C_a$ resulted on average less than half $\%C_r$ (see Table 4). This is because, according to the reconstruction process model used to calibrate such data, the long-term assistance was provided by solutions characterized by significant initial costs but able to reduce normalized costs in a long period (i.e. C.A.S.E and M.A.P.). The coefficient of variation, CoV, of $\%C_a$ resulted significantly higher in case of E rating buildings with respect to B-C ones, probably due to the significant uncertainties related to the duration of repair works and also to the influence of strengthening interventions aimed at achieving a threshold of 60% of the safety level required for new buildings (New Building Standards, %NBS), Di Ludovico et al. 2017b. This can lead to significant differences in the execution of repair/strengthening works and thus on relevant assistance to population time. For the same reason, CoV for E rating buildings resulted greater for $\%C_a$ than for $\%C_r$.

Figure 6 shows the frequency distributions and the best fitting probability density function (PDF; log-normal) of $\%C_a$ for RC (Fig. 6 a, c, e) and masonry buildings (Fig. 6 b, d, f) with reference to reconstruction classes related to E rating buildings (E-B, E_{class} and E_{dem}). The statistical parameters related to $\%C_a$ as a function of reconstruction classes are shown in Table 9. The analysis of data in terms of reconstruction class points out that the most significant mean [median] $\%C_a$ values refer to demolition and reconstruction class, that is up to 33% [30%] and 28% [23%] for RC and masonry buildings, respectively.

In light of data derived and reported in Tables 8 and 9 as well as Tables 4 and 5, it is possible to estimate a mean cost due to repair plus assistance to population (i.e. $\%C_r + \%C_a$). For instance, it turns out to be about 27% and 31% for B-C rating and about 77% and 74% for E rating RC and masonry buildings, respectively. This clearly indicate that reducing the number of severely damaged buildings not only reduces casualties but also cuts recovery costs per building of more than one third of its value.

4.3 Damage state

Figure 7 shows the frequency distributions and the best fitting probability density function (PDF) of $\%C_a$ for RC (Fig. 7a ,c, e, g, i, m) and masonry buildings (Fig. 7b ,d, f, h, l, n) as a function of the buildings DS determined based on Del Gaudio et al. 2020 and Dolce et al. 2019 conversion matrices. As for $\%C_r$, a mixture distribution (i.e. degenerate and lognormal) has been assumed to approximate the distribution of $\%C_a$ at DS1 and DS2. Note that for DS1, the probability to attain $\%C_a=0$ is 67% and 68% for RC and masonry buildings, respectively; it drastically drops down at DS2 (i.e. 8% both for RC and masonry buildings). Lognormal distributions have been assumed for DS3 and DS4 while a normal distribution and a lognormal one approximates well the distribution of $\%C_r$ at DS5.

Fig. 6 $\%C_a$ frequency distribution for RC (a, c, e) and masonry (b, d, f) buildings as a function of reconstruction class

The number of buildings belonging to each DS as well as the cumulative distribution function (CDF) of $\%C_a$ are also reported in each graph. The statistical parameters related to $\%C_a$ as a function of DSs are shown in Table 10. The data clearly show an increasing trend of $\%C_a$ with respect to DS, but less significant of that found for $\%C_r$, see Table 10. The CoV also increase by increasing DSs indicating the significant variability of population assistance time in case of severe damage.

Fig. 6 (continued)

Table 9 $\%C_a$, statistical parameters as a function of reconstruction class

	692 RC buildings			333 Masonry buildings		
Reconstruction class	E-B	Eclass	Edem	E-B	Eclass	Edem
No. of buildings	159	355	178	20	206	107
$\%C_a$ - 16 th percentile	7%	12%	14%	9%	7%	13%
$\%C_a$ - median	15%	24%	30%	12%	16%	23%
$\%C_a$ - 84 th percentile	27%	41%	51%	27%	30%	49%
$\%C_a$ mean	17%	27%	33%	17%	19%	28%
$\%C_a$ standard deviation	12%	15%	19%	10%	15%	17%
$\%C_a$ - CoV	148%	184%	171%	165%	132%	166%

5 Empirical relationship between repair and population assistance costs

The probability density functions of $\%C_r$ and $\%C_a$ can be used for the assessment of seismic loss scenarios at large scale because allow to associate repair and population assistance costs to different usability rating or damage levels, obtained by using post-earthquake data or empirical/mechanical based fragility curves. Recently, significant research efforts have been dedicated to developing loss-assessment methodologies to predict earthquake losses at the building level (Welch et al. 2012) and some refined ones focus on predictions of earthquake losses at the component level (FEMA P-58, ATC 58 2012a, implemented in user-friendly software ATC 58 2012b; Haselton and Baker 2018; Del Gaudio et al. 2019b; Del Vecchio et al. 2020). In order to provide a tool to rapidly associate at building level the direct costs expressed as repair costs to the indirect costs expressed as the portion due to population assistance costs, an empirical based relationship is presented in this section. In particular, according to data and methodologies presented (and relevant assumptions), it has been possible to associate repair costs to population assistance costs for each building of the database herein discussed, that is 7,847 buildings. The $\%C_r$ - $\%C_a$ points for RC and masonry buildings are depicted in Fig. 8 along with the best fitting of data; because the trend of points related to RC and masonry buildings are quite similar a single relationship has been herein derived.

Fig. 7 Frequency distribution of $\%C_a$ related to RC (a, c, e, g, i, m) and masonry (b, d, f, h, l, n) buildings at different damage state

The best fitting function has been calibrated on points with $\%C_r$ greater than 5% that corresponds to maximum (between RC and masonry buildings) 84th percentile $\%C_r$ on A rating buildings, see Table 4. This accounts for the no need of assistance in case of A rating buildings. Figure 8 show that a bi-linear trend can be assumed for $\%C_r > 5\%$; in particular the first linear branch (i.e. in the range $\%C_r = 5\%$ up to $\%C_r = 25\%$, that is the maximum between RC and masonry buildings 84th percentile $\%C_r$ on B-C rating buildings) has a greater inclination than the second linear branch. The best fitting bi-linear function has $R^2 = 0.28$.

Thus, a very simple tri-linear $\%C_r - \%C_a$ relationship (a first constant branch followed by two linear ones) has been determined and can be expressed as follows, see Fig. 8b:

Fig. 7 (continued)

Fig. 7 (continued)

Table 10 Percentage assistance costs with respect to reference unit costs, $\%C_a$, as a function of damage states, DS .

	4,329 RC buildings					3,518 masonry buildings				
Reconstruction class	DS1	DS2	DS3	DS4	DS5	DS1	DS2	DS3	DS4	DS5
No. of buildings	1,753	608	536	152	16	869	217	216	64	49
$\%C_a$ - 16th percentile	0%	3%	8%	11%	15%	0%	4%	7%	8%	9%
$\%C_a$ - median	0%	10%	20%	25%	38%	0%	11%	16%	19%	18%
$\%C_a$ - 84th percentile	10%	25%	37%	40%	47%	11%	24%	36%	29%	46%
$\%C_a$ mean	4%	14%	23%	27%	35%	5%	14%	21%	22%	23%
$\%C_a$ standard deviation	9%	14%	16%	15%	17%	10%	13%	15%	17%	17%
$\%C_a$ - CoV	206%	95%	71%	55%	51%	206%	93%	74%	78%	75%

Fig. 8 $\%Cr$ – $\%Ca$ relationships: tri linear trend

$$\begin{cases} \%C_a = 0 & \text{for } \%C_r \leq 5\% \\ \%C_a = 0.77C_r & \text{for } 5\% < \%C_r \leq 25\% \\ \%C_a = 0.19C_r + 0.15 & \text{for } \%C_r > 25\% \end{cases} \quad (3)$$

Although a significant dispersion of data can be observed, the relationship (3) can be used to directly estimate $\%C_a$ by only known $\%C_r$ derived by using literature available procedures.

6 Conclusions

This paper illustrates the relationships between empirical damage and direct/indirect losses on residential reinforced concrete and masonry buildings. The relationships have been derived from a database of 8,497 buildings damaged by L'Aquila 2009 earthquake. In particular, probability density functions and relevant statistics have been determined to correlate repair costs and population assistance costs (expressed in terms of percentage of

cost with respect to the reference unit cost of a new building, $\%C_r$ and $\%C_a$) as a function of buildings damage. The damage is expressed in several ways: usability rating (A, B-C or E usability rating for undamaged, lightly or severely damaged buildings); reconstruction classes (class E-B, including buildings with a high non-structural damage but with slight structural damage; E_{class} including buildings with severe structural damage, and E_{dem} , including buildings that needed to be demolished); global damage states according to European Macroseismic Scale (EMS-98), DS, from DS1 to DS5 determined on the basis of literature available rules to convert empirical damage to structural and non-structural components into building global damage. The $\%C_r$ frequency distributions were derived from repair intervention costs computed by practitioners engaged by property owners to apply for public grant for reconstruction, while $\%C_a$ were obtained by using a methodology developed to associate population assistance time and costs to single buildings. The relationships between costs and usability performances of buildings are particularly suitable in the immediate post-earthquake to rapidly estimate reconstruction costs, while those between costs and damage states represent a crucial tool to define territorial scale loss scenario by using empirical or mechanically based fragility curves.

Furthermore, an empirical based relationship has been calibrated to directly correlate repair costs on a building with assistance costs to their occupants which could be an essential tool to fully exploit the potential of available literature methods to provide refined estimation of repair costs at building level.

The main findings of this study are:

- mean [median] $\%C_r$ resulted 2% [0%], 14% [12%], 51% [43%] for A (usable), B-C (unusable with light structural damage), E rating (unusable with severe structural damage) RC buildings and 2% [0%], 16% [14%], 52% [42%] for A, B-C, E rating masonry ones; the coefficient of variations, CoV, of E rating buildings were generally lower than that related to B-C rating ones due the high variability of costs related to actions aimed at restoring non-structural components;
- a significant portion of E rating buildings, about one-third, were demolished, E_{dem} reconstruction class, because economically convenient due to $\%C_r$ close to 100%;
- according to matrices adopted to convert empirical damage on components to a global building damage state, DS, resulted that: A rating buildings mostly belongs to DS0 or DS1; B-C rating to DS1 or DS2; E rating to DS3; damage states DS4 and DS5 attains their peak values in the case of E_{dem} reconstruction class;
- the best fitting probability density functions of $\%C_r$ as a function of DS for RC and masonry buildings resulted a mixture of a degenerate (discrete) and lognormal (continuous) distribution for DS1-DS2, a mixture of two lognormal distributions for DS3-DS4, and a normal (RC buildings) or a mixture of normal and lognormal distributions (masonry buildings) for DS5; mean [median] $\%C_r$ from DS1 to DS5 resulted 6% [3%], 19% [14%], 39% [34%], 62% [59%], 78% [81%] for RC buildings and 8% [4%], 22% [17%], 41% [33%], 59% [52%], 67% [72%] for masonry buildings;
- the average cost per month per person, C_i , to assist people in different accommodation types resulted: €1191,20 for tents; €1524,40 for hotels; and €227,40 for s.a.g. (self-accommodation grant); € 581.70 for C.A.S.E. (Anti-seismic, Sustainable and Ecologically Compatible Housing Complexes) project; and € 350.20 for M.A.P. (Temporary Inhabitable Modules);
- mean [median] $\%C_a$ resulted on average comparable to mean [median] $\%C_r$ for lightly damaged buildings (i.e. B-C rating) while on average resulted less than half $\%C_r$ in case of severely damaged buildings (i.e. E rating);

- the best fitting probability density functions of $\%C_a$ as a function of DS resulted a mixture of a degenerate and lognormal distribution for DS1–DS2, lognormal distributions for DS3–DS4, and a normal (RC buildings) or lognormal distribution (masonry buildings) for DS5; mean [median] $\%C_a$ from DS1 to DS5 resulted 4% [0%], 14% [10%], 23% [20%], 27% [25%], 35% [38%] for RC buildings and 5% [0%], 14% [11%], 21% [16%], 22% [19%], 23% [17%] for masonry buildings;
- CoV of $\%C_a$ increases by increasing DSs indicating the significant variability of population assistance time in case of severe damage;
- a simple empirical based relationship to associate repair costs to population assistance costs for each building can be expressed by using a tri-linear relationship: $\%C_a = 0$ for $\%C_r < 5\%$; $\%C_a = 0.77\%C_r$ for $5\% \leq \%C_r \leq 25\%$; and $\%C_a = 0.19\%C_r + 0.15$ for $\%C_r > 25\%$.

The above results are drawn from data relevant to a single event, which also means a specific model of assistance to the population (tents, MAP, CASE, s.a.g.). Different models adopted for different events and in different socio-economic conditions can obviously lead to different results. Further data are therefore needed to provide more reliable and robust relationships or even relationships relevant to different models of population assistance. However, the unique and comprehensive data presented provided the opportunity to derive useful relationships to perform loss scenarios and drive decisions makers involved in the definition and planning of suitable seismic risk mitigation policies.

Acknowledgments This study was performed within the framework of the PE2019–2021 joint program DPC-ReLUIS, WP4: “Seismic Risk Maps—MARS”, Task 4.4. “Risk: evaluation of consequences and economic losses”.

Funding Open access funding provided by Università degli Studi di Napoli Federico II within the CRUI-CARE Agreement.

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