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DEVELOPING STOREY LOSS FUNCTIONS FOR EVALUATION OF SEISMIC RISK IN ITALIAN RESIDENTIAL BUILDING TYPOLOGIES

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Abstract

Refined and simplified methodologies are generally used to perform seismic loss assessment of existing buildings. The refined methodologies typically refer to probabilistic component-based approaches, which are difficult to be implemented by practitioners. A reliable alternative could be the use of storey loss-based frameworks, which although less complex, still require some improvements in the calibration of its input elements to avoid overly conservative loss estimates. This paper deals with the development of generalised storey loss functions (SLFs) for different Italian residential building typologies, using post-earthquake observational damage data from the 2009 L'Aquila earthquake. Data on real buildings was collected from the Italian price bulletin to ensure that both the building typologies and the cost ratios for structural and non-structural components, with respect to the total construction cost, can be effectively representative of the real features of Italian residential buildings. At the same time, the SLFs were developed as a function of the building's replacement value, estimated using the current average construction cost per square metre in Italy. The adopted fragility models were specifically calibrated for structural and non-structural components commonly found in Italian and Mediterranean-country reinforced concrete buildings. The assumed repair costs were incurred after the 2009 L'Aquila earthquake. The proposed SLFs can be a useful alternative to the simplified conservative loss assessment guidelines currently employed in Italy to plan risk mitigation measures at regional and single-building levels.

Keywords: Storey loss functions, Residential buildings, Building portfolio, Simplified loss assessment.

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1 INTRODUCTION

In the last decades, significant research efforts have focused on the development of simplified methodologies to perform seismic loss assessment for existing structures. Different simplified approaches relating the economic losses to specific engineering demand parameters (EDP) were thus developed to significantly reduce the computational onus and to be used as a more user-friendly tool for practitioners and stakeholders to conduct building-specific loss assessment.

The Displacement-Based Assessment (DBA) procedure, firstly introduced by Priestley [1], was extended by Crowley et al. [2] to the estimation of the expected annual losses (EAL), proposing the Displacement-Based Earthquake Loss Assessment (DBELA) framework. DBELA enabled the loss assessment of large building stocks, due to its simplified assumptions that cover different structural typologies, rendering it useful mainly at regional/national scale. Subsequently, Ramirez and Miranda [3], with a view to derive a widespread code-based procedure for practitioners, developed the storey loss functions (SLFs) approach, reducing the probabilistic complexity and computational effort of the well-known PEER-PBEE methodology [4]. The SLF approach is based on engineering demand parameter versus decision variable (EDP-DV) functions, directly relating the EDPs to economic losses; these functions are generally specific for every storey level and therefore termed storey loss functions. Another approach was explored by Sullivan and Calvi [5] and, later on, by Welch et al. [6], for seismic loss assessment at the building-specific level, again based on direct displacement-based assessment (DDBA) principles. The EAL estimates obtained through DDBA were shown by Welch et al. [6] to be close to those obtained with the PEER methodology. More recently, Cardone et al. [7] used, under specific assumptions, a closed-form equation to estimate the EAL of a single building, reducing the aforementioned probabilistic complexity to perform large-scale seismic loss assessment. The approach, termed DEAL (Direct estimation of Expected Annual Loss), overcomes the limitations associated with assuming given loss factors for selected limit states and has the capability of considering building irregularity in height and different occupancy types. Finally, an even more simplified approach, known as SismaBonus, originated the seismic risk classification guidelines [8], recently introduced in Italy to estimate the seismic risk of existing buildings. This framework provides a straightforward risk classification system based on two parameters: a life safety index (SI-LS) and the EAL. The latter is computed starting from the performance of the structure for different return periods Tr, expressed in terms of the mean annual frequency of exceedance ($\lambda = 1/Tr$) and assigning each damage state to a pre-defined repair cost, expressed as a percentage of the reconstruction cost. However, as observed by O'Reilly et al. [9] and Perrone et al. [10], although its simplicity encourages practitioners to use it, its EAL predictions can largely overestimate those obtained with the component-based PEER-PBEE approach. Such inaccuracy was noticed for buildings characterised by drift/acceleration profiles or structural/non-structural element distributions that differ in the two main directions or along the building height.

Considering the above, there is still a need to develop practical tools for building-specific loss assessment that can be used by practitioners or decision-makers in general that are not overly conservative with respect to more accurate, yet complex, approaches. Accordingly, this study develops and proposes generalised storey loss functions for seismic loss assessment of Italian residential buildings, using a database of 120 RC residential buildings damaged by the 2009 L'Aquila earthquake, which were classified through the AeDES forms [11] in the immediate aftermath of the event. While the Italian seismic risk classification guidelines neglect the correlations between damage and type of components (ignoring the specific EDP to which the non-structural elements are sensitive), the EDP-DV functions proposed herein allow to directly relate the EDPs to economic losses, thus taking into account the structural response, e.g., influenced by the presence of the masonry infills along the building height [12]. Moreover, they are calibrated using post-earthquake observational damage data of the 2009 L'Aquila earthquake thus guarantee a much sounder quantification of the EAL. The proposed SLFs can be also combined with one of the aforementioned recent simplified frameworks [10], using e.g. the N2 method [13] to derive the main input parameters for loss estimation.

2 RESEARCH METHODOLOGY

The Italian seismic risk classification guidelines [8], also known as SismaBonus, are currently used for estimating the seismic risk of existing buildings. The advantage of the framework is its probabilistic simplicity, not computationally expensive, allowing it to become popular in the engineering practice field. It is easily implemented by structural engineers, who are already familiar with linear static/dynamic analysis and nonlinear static analysis, as well as with the technical principles of current standards for seismic design/assessment of buildings at different Limit States (LSs). The framework introduced, in a practical manner, the use of EAL and two conventional LSs, namely Initial Damage (IDLS) and Reconstruction (RLS), to estimate the losses. The repair costs of structural and non-structural elements (NSEs) provided in FEMA E-74 [14] were used in the SismaBonus calibration, while the validation process was carried out using the repair costs incurred for repairing the buildings damaged during the 2009 L'Aquila earthquake. As mentioned in the Introduction, although its simplicity encourages its use in current practice, a few shortcomings can be pointed out: (i) EAL overestimation and (ii) neglection of the specific level of damage to structural and NSEs, due to non-consideration of the EDP to which the components are sensitive.

To address these limitations, the methodology adopted in this study derives SLFs for seismic assessment of Italian residential buildings, building upon another simplified framework [3] for loss assessment, while still guaranteeing a simplified nature, to be used by practitioners. To do so, the methodological framework addresses different issues, to propose ready-to-use functions, related to: (i) quantification of building construction or replacement cost, (ii) quantification of structural and NSEs, (iii) selection of appropriate fragility curves for structural and NSEs, and (iv) definition of the repair costs for structural and NSEs. In specific, these issues are overcome by the adopted research methodology, depicted in Figure 1, through the following features:

- Selection of 15 RC residential buildings from the Italian price bulletin of building typologies [15]. The selected building typologies were chosen to cover a wide range of possibilities: subsidized housing, single-family houses, medium-high quality buildings, terraced houses and tower buildings, for which detailed construction costs for structural and NSEs were provided. According to the economic value of the structural and NSEs in the building, the building set was equally subdivided into three groups, resulting in an average construction cost of 880€/m^2, 1212€/m^2 and 1527€/m^2 for low, medium and high building value, respectively;
- Five component categories were defined: structural components, infills and partitions, plumbing and electrical systems, windows/doors and other NSEs. For each building type and component category, the NSEs were identified, defining both the monetary value of each category and the percentage of incidence with respect to the total construction cost;
- Realistic repair costs were assigned to each damage state (DS), using those incurred for repairing the buildings damaged during the 2009 L'Aquila earthquake. The distributions

of costs (mean and standard deviation) for each DS, as well as the repair costs [16] at the component level, distinguishing between drift, acceleration and drift/acceleration sensitive components, were determined following the damage classification defined through the AeDES forms [10];

- Fragility curves for structural components, associated with each of the sequential DSs, specifically calibrated for common Italian and Mediterranean RC buildings, were used [17]. The fragility curves proposed by Cardone and Perrone [18] were in turn adopted for masonry infills and partitions. The damage to windows and doors was conditioned to the damage of the masonry infills, whereas the fragility functions proposed in FEMA P-58 [19] were used for all the acceleration-sensitive NSEs.

SLFs for each component category were then obtained using the Python-based toolbox proposed by Shahnazaryan et al. [20], adopting a Weibull cumulative distribution function to perform the regression analysis, whose accuracy was assessed through the estimation of maximum and cumulative relative regression errors over the EDP range for each component category.

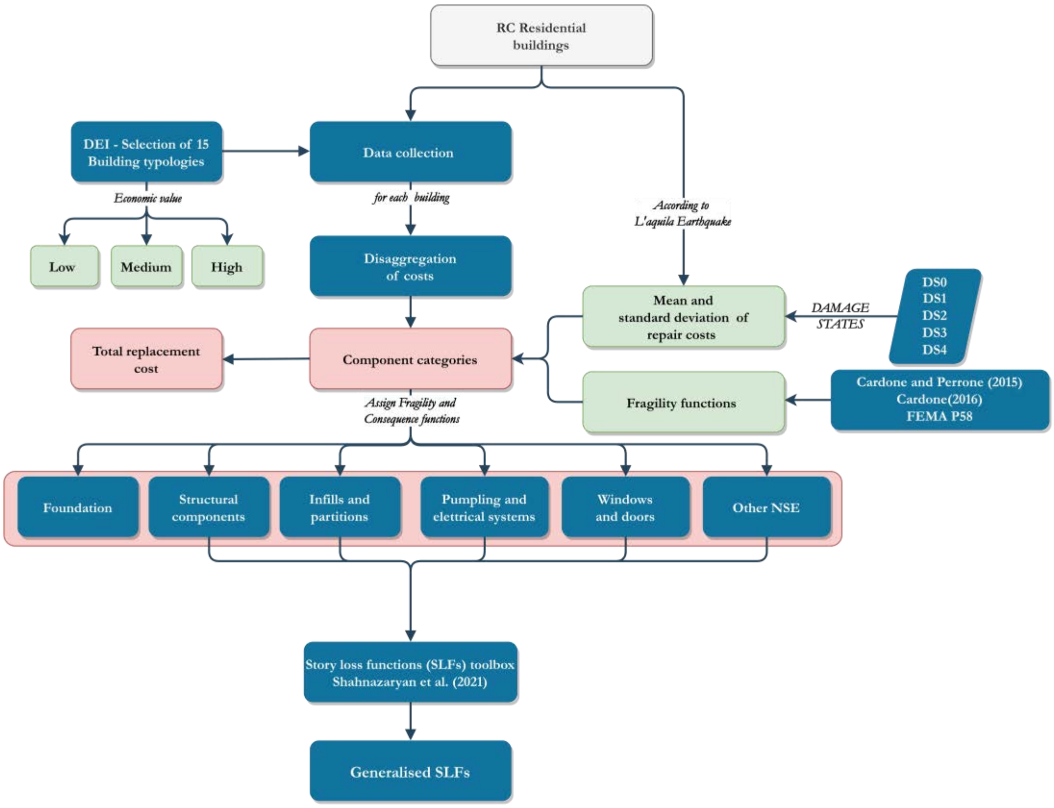

Figure 1 Research Methodology

3 BUILDING DATA COLLECTION

Given the high percentage of residential buildings in Italy (about 84% of the Italian building stock), as highlighted by the Italian census database ISTAT [21], this study focuses on these building typologies for the SLF development.

3.1 Definition of representative building typologies

To quantify the building construction cost, 15 buildings were selected from the Italian price bulletin of building typologies, put together by the Order of Engineers and Architects of Milan (Italy) [15]. Such a document collects different building types and provides real examples of buildings in the Lombardy region, together with the associated construction and components cost. The construction costs were updated to 2019 according to public works pricelists [22] of the Lombardy region and are inclusive of overhead and contractor's profit, with the exclusion of the following costs: land, professional fees, planning and services (gas, electricity, etc.) fees, arrangements of outdoor spaces. The selected building typologies were chosen to cover a wide range of possibilities: subsidized housing, single-family houses, medium-high quality buildings, terraced houses and tower buildings, for which detailed construction costs for structural and NSEs were provided in DEI [15]. The cost of materials and labour, earthmoving and landfill, amongst different others, might be different from one city to another and a generalisation at national level should account for such variability in the costs.

3.2 Identification of component categories

The accurate evaluation and quantification of all structural and NSEs for each building was ensured taking the actual executive bill of quantities [15]. Given that the data was disaggregated in different construction works, it was necessary to identify six component categories, according to which the structural and NSEs were collected. This grouping enabled the use of the actual repair costs incurred when repairing the buildings damaged during the 2009 L'Aquila earthquake, which were available for each DS in those specific component categories, namely:

(i) ***foundations***: all the costs related to excavations and backfills, earthmoving work, geotechnical surveys and diaphragm construction were considered. These costs were defined for completeness only and actually not used for the development of the SLFs, however they should be accounted for in the total replacement costs, in case of building collapse or when it must be demolished;

(ii) ***structural components***: all costs related to the construction of RC members and floors were considered, including formworks;

(iii) ***infills and partitions***: all costs related to the construction of external infills and internal partitions, thermal insulation (if any), internal and external plastering, painting and any decorative elements or façade finishings were taken into account;

(iv) ***plumbing and electrical systems***: all costs related to the construction of electrical and plumbing heating/cooling systems, fire protection and gas systems, were considered;

(v) ***windows and doors***: all costs related to the construction of interior and exterior fixtures, wood, marble and ironwork, cladding and skirting boards were considered;

(vi) ***other NSEs***: all costs related to the construction of roofs and chimneys, lift, sanitary system, stair finishes, lighting, rain drainage were taken into account.

3.3 Quantification of construction and component costs per building typology

Figure 2a provides a summary of the construction costs for each of the selected building typologies and their disaggregation for each component category. The lower and higher construction costs are 766€/m^2 and 1881€/m^2, respectively, while the mean and median construction costs are 1206€/m^2 and 1216€/m^2, respectively. The mean and median construction costs obtained herein are similar to the total financing (1213.40 €/m^2) provided by the Italian government for building demolition and reconstruction of assets classified as unusable according to the AeDES forms [11]. Figure 2a also clarifies how the construction costs of each component category change between different building typologies, which introduces additional uncertainties on the quantification of generalised repair costs and on pre-defined SLFs. As such, the 15 selected buildings were subdivided in three main categories (low-, medium- and high-value) - five buildings per category - resulting in an average construction cost for each category of

880€/m^2, 1212€/m^2 and 1527€/m^2 (Figure 2b). Such mean aggregated construction costs are very close to the 16th (847€/m^2), 50th (1216€/m^2) and 84th (1467€/m^2) percentiles of the construction cost distribution of the entire building set.

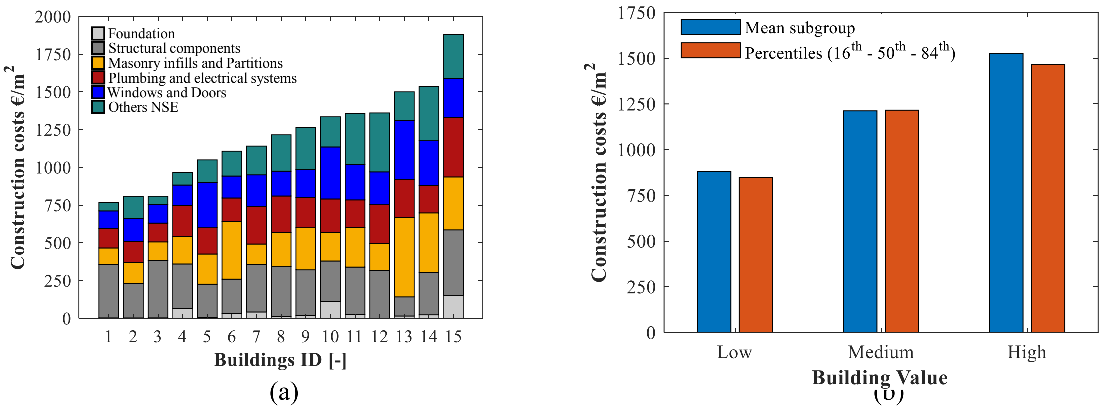

Figure 2 (a) Building typologies selected and disaggregation of construction costs for each component category, and (b) construction cost for low-, medium- and high-value buildings.

4 DEVELOPMENT OF STOREY LOSS FUNCTIONS

4.1 Fragility functions

The generation of specific SLFs for a single building or building class requires the classification of the structural and NSEs in performance groups based on the EDP to which their damage is more sensitive, along with the definition of the corresponding fragility functions. In cases for which the component category is sensitive to both the EDPs, such as infills and partitions, SLFs are developed herein considering both possibilities.

Regarding the fragility functions for structural components (component category 1) [17], they were chosen to consider the common deficiencies that can be found in existing gravity load-designed RC buildings in Italy, including detailing of beam-column joints, possible bar slippage, insufficient anchorage and interaction between masonry infills and the surrounding frame.

The fragility curves for component category 2 (infills and partitions) were taken from the work of Cardone and Perrone [18]. In addition to the in-plane (IP) behaviour of the masonry infills, such a study also pointed out the possible out-of-plane (OOP) failure of masonry infills and partitions, and, consequently, proposed PFA-based collapse fragility functions, associated with OOP collapse of masonry infills. Considering the importance of both possible failure modes, SLFs of infills and partitions for both EDPs were developed herein, assuming that the total losses in case of collapse of the infill and partition are the same, regardless of the EDP that triggered collapse. Moreover, depending on the structural response in terms of IDR and PFA for each intensity measure (IM) level, the losses produced by one or the other EDP are both accounted for, conservatively keeping the one that produces higher economic losses at a given IM level.

The fragility curves for component category 3 (plumbing and electrical systems) are defined as acceleration-sensitive in FEMA P-58-1 [19]. This is related to the assumption that such components run through and are connected to the suspended ceilings, which are actually acceleration-sensitive NSEs. Considering the specific construction typologies in Italy, the damage to plumbing and electrical systems is assumed as conditioned to that of masonry infills and partition walls (which are drift/acceleration-sensitive NSEs); such assumption was made considering the lack of appropriate correlation models between damages of component category 2 and those of component category 3, as well as no IDR-based fragility functions available for component category 3. As such, given that there could be specific cases in which the damage to component category 3 may be sensitive also to accelerations, the SLFs were developed for both EDPs. For the drift-sensitive NSEs, the fragility curves assigned to the infills and partitions were used, whereas for the acceleration-sensitive NSEs, the fragility functions proposed by FEMA P-58 [19] were adopted.

A similar situation is found for component category 4 (windows and doors) - their damage is conditioned to that of masonry infills and partition walls thus the fragility functions of component category 2, which are fitted to IDR, were used also for the components in category 4. Finally, the fragility functions proposed by FEMA P-58 [19] were used for all the components belonging to category 5 (other NSEs), which are acceleration-sensitive.

4.2 Repair costs

The definition of the repair costs needs to account for specific features of the NSEs, together with the cost of materials and labour, the repair/restoration difficulties, amongst many others, which might be very different from one country to another. In this regard, Silva et al. [23] pointed out that simply adopting repair cost data for other parts of the world introduces significant uncertainty, highlighting the differences in costs between the US and European countries. In fact, FEMA P-58 [19] is largely US-oriented with costs and component typologies corresponding to those typically found in California, hence it was not used herein. Two alternatives can be adopted: (i) to estimate the repair costs based on public work pricelists, containing the costs of construction and reparation of common civil structures or (ii) to use collections of repair costs incurred after real earthquake events.

The first should be the most accurate option, providing updated prices per repair item, however, it does not provide an estimate per m^2 and requires an estimate of the number of components in the building for each specific repair intervention, making it difficult to even use the data of total construction costs and of component categories available per m^2 in Del Vecchio et al. [16], as reported in Section 3. Moreover, such an approach would somehow drift apart from one of the advantages of the SLF framework, which would enable loss estimation even if much of the building's inventory is uncertain or unknown.

The other option would be to use the repair costs incurred for repairing the buildings damaged during the 2009 L'Aquila Earthquake. Such costs are expressed per m^2 and were detailed by Del Vecchio et al. [16], providing the repair cost distributions and the correlation with observed earthquake damage at both the building and component levels. An advantage of using the data provided by Del Vecchio et al. [16] is that it is expressed in terms of repair cost per m^2 and classified per component category (drift, acceleration and drift/acceleration sensitive components), thus consistent with the development of generalised SLFs. A limitation to the use of this data is related to several socioeconomic phenomena incurred in the reconstruction process after the L'Aquila earthquake, as reported by different sources [23-25], which have affected the measured repair cost. One of those aspects, which produced an increase in the observed costs, was the governmental decision-making process that paid for the repair and strengthening of damaged assets. Moreover, the L'Aquila repair cost data was used to calibrate the Italian seismic risk classification guidelines [8], SismaBonus. For this reason, this was the repair cost quantification option adopted herein for the SLF definition.

The damage classification following the L'Aquila earthquake was carried out through the AeDES forms [11], which were then used to define the distributions of costs (mean and standard deviation) for each damage state, as well as to define the repair costs at component level, distinguishing between drift, acceleration and drift/acceleration sensitive components [16]. A summary of the mean repair cost and dispersion, as a function of the damage state, for each component category, is provided in Figure 3. The repair costs in Figure 3 do not include those related to construction field installation, safety measures and professional fees, to ensure consistency with the total construction costs (or replacement costs) provided in Section 3, which excluded land, professional fees, planning and service connection (gas, electricity, etc.) fees, and arrangement of outdoor spaces.

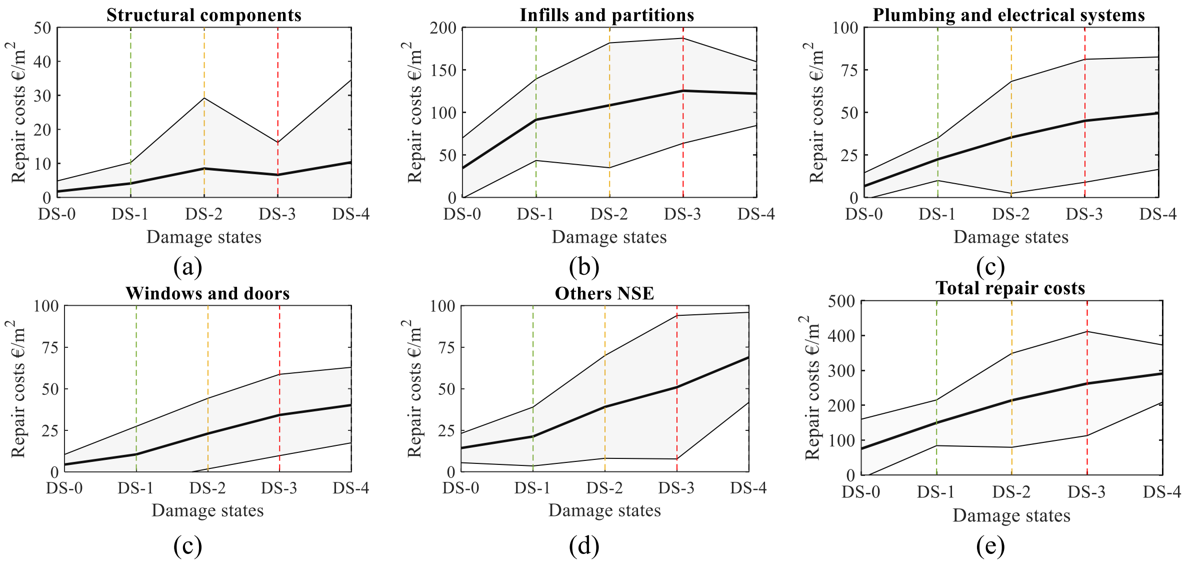

Figure 3 Mean (black) and standard deviation (filled area) of the repair cost, as a function of the damage state: (a) structural components, (b) infills and partitions, (c) plumbing and electrical systems, (d) windows and doors, (e) others NSE and (f) total repair costs of all the structural and NSEs.

The analysis of the repair costs shows that the majority involve the repair intervention of infills and partitions, with a mean repair cost of about 50% of the building total repair costs, ranging from 42% to 62%, as a function of the DS. Moreover, since both plumbing/electrical systems and windows/doors are incorporated in the infills and partitions, the mean repair cost, considering also these other categories of NSEs, rises rapidly to about 74% of the building total repair costs, ranging from 61% to 83%, depending on the damage severity. The repair costs for structural components are, in turn, very low when compared to the NSE ones, whereas the other NSEs, such as roofs and chimneys, stair finishings, lighting, sanitary systems, rain drainage, present repair costs that range from 14% to 24% of the total repair costs, with a mean value of 19%.

Accordingly, for the development of SLFs, the repair cost for each component, at each sampled damage state, was quantified based on the data provided in Figure 3, through random sampling from the repair cost distributions thus considering the related uncertainty.

4.3 Storey loss functions

The SLFs for component groups were obtained through regression analysis on the normalised sampled repair costs, fitting a Weibull cumulative distribution function to the data, as per Equation 1:

$$y = \alpha\left(1 - e^{-\left(\frac{x}{\beta}\right)^{\gamma}}\right) \tag{1}$$

where α, β and γ are the fitting coefficients, x is the EDP value, and y is the fitted loss ratio value.

The goodness of the regression is then gauged through the estimation of the maximum ($error_{max}$) and cumulative ($error_{cum}$) relative regression errors over the EDP range for each component performance group, according to Equations 2 and 3:

$$\mathrm{error}_{\max} = max\left(\frac{\left|C_{repair}^{EDP} - \hat{C}_{repair}^{EDP}\right|}{max\left(C_{repair}^{EDP}\right)}\right) \tag{2}$$

$$\mathrm{error}_{\mathrm{cum}} = \int_{0}^{EDP=max\,EDP} \mathrm{error}_{\max}\, dED = \int_{0}^{EDP=max\,EDP} max\left(\frac{\left|C_{repair}^{EDP} - \hat{C}_{repair}^{EDP}\right|}{max\left(C_{repair}^{EDP}\right)}\right) dEDP \tag{3}$$

where C_{repair}^{EDP} and $\hat{C}_{repair}^{EDP}$ are the original and fitted repair costs, respectively.

The SLFs developed herein present maximum and cumulative relative regression errors over the EDP range, for all the component categories, that are always less than 2% and 4%, respectively. The resulting fitting coefficients, for each component category, are summarised in Table 1, whilst the 16^{th}, 50^{th} and 84^{th} percentiles and the mean α, β and γ coefficients are provided in Figure 4.

Table 1 Summary of the fitting coefficients of the Weibull distribution for all the component categories.

Component category	**16th**			**50th**			**84th**			**Mean**		
	α	β	γ	α	β	γ	α	β	γ	α	β	γ
Structural components IDR [%]	0.81	1.84	1.52	0.91	1.56	1.27	0.91	1.21	1.16	0.94	1.42	1.20
Infills and Partitions IDR [%]	0.87	0.83	0.84	0.90	0.69	0.76	0.92	0.57	0.67	0.94	0.65	0.73
Infills and Partitions PFA [g]	0.95	0.93	23.63	0.97	0.67	15.24	0.97	0.51	7.67	0.97	0.70	3.37
Plumbing and electrical systems IDR [%]	0.83	0.69	0.95	0.91	0.61	0.91	0.90	0.51	0.84	0.93	0.57	0.87
Plumbing and electrical systems PFA [g]	0.83	1.10	2.42	0.91	1.03	2.07	0.91	0.79	2.27	0.92	0.91	2.06
Windows and doors IDR [%]	0.74	1.74	6.15	0.89	1.20	5.09	0.91	0.87	4.64	0.92	1.15	2.77
Other NSEs PFA [g]	0.85	2.02	3.71	0.90	1.89	2.81	0.88	1.73	2.39	0.92	1.83	2.60

The SLFs expressed in terms of repair cost (Figure 4) can also be normalised by the replacement cost, as illustrated in Figure 5, using the disaggregation of construction costs for each component category, for all the 15 selected buildings. The 16^{th}, 50^{th} and 84^{th} percentiles of the normalised SLFs are also shown, providing information on the variability of the repair vs replacement costs of the components in the buildings. The median repair cost for the structural components is, at most, close to 7% of the replacement cost whereas, for what concerns the NSEs, the higher ratio between repair and replacement cost is observed for infills and partitions, with a median value of about 0.95; for other NSEs, plumbing/electrical systems and windows/doors the median ratio is of about 0.42, 0.30 and 0.20 respectively.

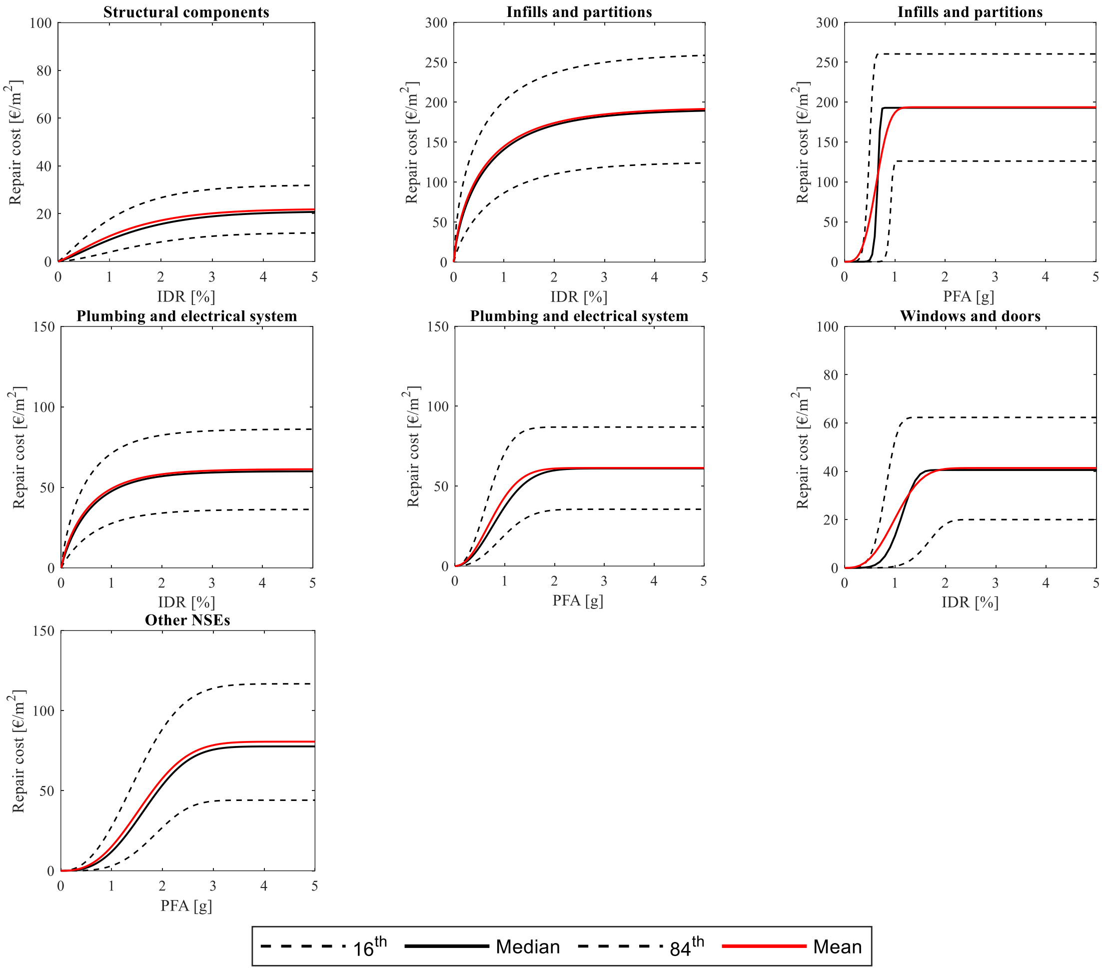

Figure 4 Proposed storey-loss functions (SLFs) for each of the component category.

5 CONCLUSIONS

This study presented the development of generalised storey loss functions (SLFs) for seismic assessment of Italian residential buildings. A detailed analysis of the Italian price bulletin of building typologies was used to define the total construction costs and the cost ratios for structural and non-structural elements with respect to total construction costs, for different Italian residential buildings. Different building values were identified (subsidized housing, single-family houses, medium-high quality buildings, terraced houses and tower buildings) and, accordingly, generalised SLFs were developed considering the building's replacement value, estimated using the current average construction cost per square metre.

The repair costs incurred in the reconstruction process following the L'Aquila Earthquake were used to guarantee SLFs as realistic as possible, i.e., in accordance with real repair costs effectively incurred after a seismic event. Fragility functions specifically calibrated for structural and non-structural elements commonly found in Italian and other Mediterranean RC buildings were adopted, considering the specific construction features of such buildings.

One of the main advantages of using SLFs is that the structural responses (monitored through the engineering demand parameters) affect the damage quantification and consequently the expected annual loss estimates are more accurate. Indeed, by using SLFs, the structural response, e.g., influenced by the presence of the masonry infills with and without openings, along the building height, could be strictly correlated to the damage. The proposed SLFs can serve as an alternative to the simplified conservative loss assessment guidelines currently employed in Italy, while still usable and easily implementable by practitioners or decision-makers and researchers in general, for simplified seismic loss assessment.

Future developments of this study will also consider the development of SLFs for different residential building typologies (diversifying the SLFs between those at intermediate floors and roof) and considering a higher number of seismic events for the estimation of both damage states and corresponding repair costs, for which both the post-earthquake damage surveys and reconstruction costs are available. Moreover, generalised "environmental storey loss functions" (eSLFs), i.e., expected environmental losses due to the damages and the consequent repairing/rehabilitation phase, which have not yet been proposed, will be investigated towards an integrated estimation of seismic and environmental impact–related losses.

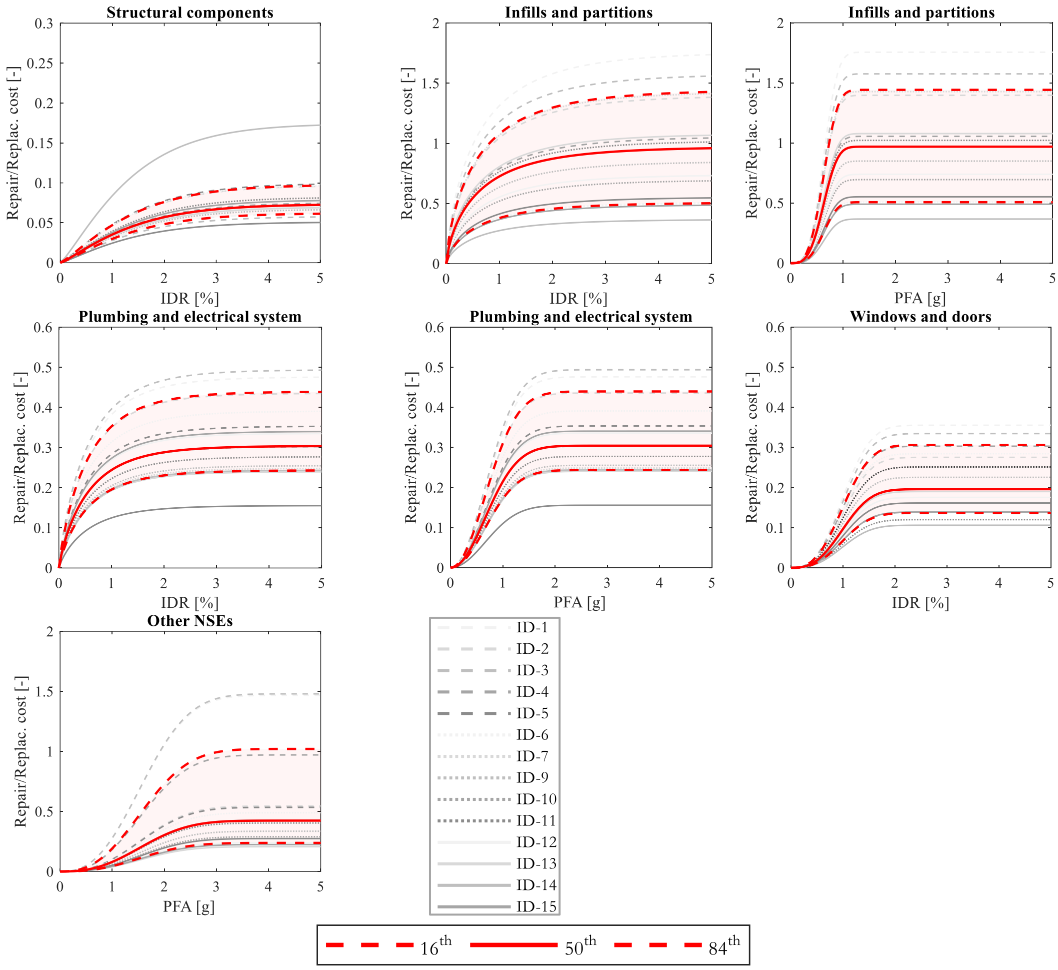

Figure 5 Normalised storey loss functions (SLFs) for each component category.

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