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DEVELOPING STOREY LOSS FUNCTIONS FOR PORTUGUESE RC BUILDINGS

R. Couto[1], G. Mucedero[2], R. Bento, and R. Monteiro[2]

[1] University School for Advanced Studies IUSS Pavia, Pavia, Italy
{rita.couto,gianrroco.mucedero,ricardo.monteiro}@iusspavia.it

[2] CERIS, Instituto Superior Técnico, Universidade de Lisboa, Lisbon, Portugal
rita.bento@tecnico.ulisboa.pt

[3] CONSTRUCT, Faculty of Engineering, University of Porto, Portugal
rncm@fe.up.pt

Abstract

Storey loss functions (SLFs) are among the most refined, yet simplified, tools to estimate seismic economic loss that can replace highly computationally intensive and time-consuming approaches, like the PEER-PBEE methodology. A key advantage of SLFs is the faster disaggregation of losses associated to drift- or acceleration-sensitive, structural or non-structural components, supporting decision-makers to identify effective retrofitting strategies that can significantly reduce the overall seismic risk. Furthermore, they can be integrated with an equivalent SDOF modelling approach to more accurately compute economic losses on a large scale. Nevertheless, SLFs are still not available for many European countries, thus limiting their use in large-scale risk assessment studies. To overcome this gap, SLFs tailored specifically for the Portuguese RC building stock are proposed in this study, derived from typical architectural layouts of RC buildings, and combining available fragility models with component repair/replacement cost estimates grounded in the Portuguese context. This approach offers a practical alternative to more complex, full-building seismic loss assessments, simplifying the evaluation of damage and economic impacts across several buildings, and providing a valuable tool to support future seismic risk assessment studies in Portugal.

Keywords: Simplified risk assessment, Storey loss functions, RC buildings

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1 INTRODUCTION

Storey loss functions (SLFs) are rapidly emerging as one of the most refined, yet simplified, tools for estimating seismic economic losses, effectively replacing more computationally demanding methods, such as the PEER-PBEE methodology [1]. One of the key advantages of SLFs is their ability to disaggregate losses in terms of drift- or acceleration-sensitive structural and non-structural components. This allows for a faster and more efficient identification of loss contributions, which can help decision-makers and stakeholders in selecting effective retrofitting strategies to reduce overall seismic risk. Moreover, SLFs can be integrated with simplified single degree of freedom (SDOF) building models, enabling faster and computationally feasible seismic loss assessment studies at a large scale [2].

Several studies have explored the development and application of simplified seismic loss estimation methods, particularly through the use of SLFs. Shahnazaryan et al. [3] introduced a Python-based toolbox designed to facilitate the creation of SLFs, offering a streamlined alternative to traditional component-based loss estimation methods. The practical application of SLFs was demonstrated through a case study, highlighting their ability to provide accurate results while being more time-efficient and user-friendly for practitioners. Papadopoulos et al. [4] expanded on the concept of SLFs by leveraging resources from FEMA P-58 [1]. Through a case study of low- to mid-rise steel office buildings, this study demonstrated how this simplified method can efficiently quantify potential seismic losses without requiring exhaustive data on individual building components. Mucedero et al. [5] focused on the development of general SLFs for existing reinforced concrete (RC) residential buildings in Italy, using post-earthquake damage data from the 2009 L'Aquila earthquake. The proposed SLFs were then applied to a representative portfolio of Italian buildings, and the results were compared to those of previous studies. This comparison confirmed the consistency of their SLF-based methodology and validated its effectiveness in estimating seismic losses for residential buildings, demonstrating its potential for widespread application in both academic research and practice assessments.

Despite these studies, SLFs have not yet been widely developed for many seismic-prone European countries, limiting their applicability for broad-scale risk assessments. Focusing on Portugal, there is a lack of specific SLFs tailored to the unique building typologies and seismic characteristics of the country, limiting seismic risk assessment studies. This study addresses such a gap by analysing typical architectural layouts of RC buildings built before 1980 and combining available fragility models with component-specific repair and replacement costs that reflect the Portuguese context. Although fragility functions specific to Portuguese components are not available, those from other studies were employed, assuming the components share similar characteristics. A comparable approach was adopted for consequence functions, using repair costs from existing literature, adjusted for inflation and construction dynamics through appropriate conversion factors. Moreover, by incorporating various sources of fragility and repair cost data, the uncertainty surrounding SLF estimates is better characterised, capturing the variability in construction practices, geographic location, and building typologies. The proposed SLFs provide a streamlined and more efficient alternative than detailed component-based loss assessment, offering a practical tool for evaluating damage and economic impacts across a wide range of building types, towards the reduction of potential economic losses.

2 METHODOLOGY

The derivation of SLFs starts with detailed data collection of the building's storey component inventory, including the corresponding fragility functions and repair costs associated with each damage state. Components are categorised based on their sensitivity to different engineering demand parameters (EDPs), thus generally distinguished between drift-sensitive and acceleration-sensitive elements. Moreover, SLFs can be developed for all components within a storey by either grouping them according to their EDP sensitivity or organising them into distinct categories, while still considering their EDP sensitivity. The latter provides a clearer understanding of the contribution of each category to the overall economic loss of the storey. The key steps involved in the development of storey loss functions are:

i. **Building characterisation:** this step includes identifying key attributes such as the structural system, occupancy type, and period of construction, which significantly influence both fragility assessment and repair cost estimation. Additionally, the characterisation should incorporate regional construction practices, material properties, and potential design deficiencies to ensure a realistic representation of the building's performance under seismic actions.

ii. **Inventory of building components:** compile a detailed inventory of all structural and non-structural components within a building that are susceptible to damage and contribute to economic losses. This information can be obtained through statistical analyses of existing buildings, market surveys, or, when more precise data is unavailable, expert judgment or established guidelines. The inventory can handle different floor levels, each with its own set of components. The outcome of this process is a comprehensive inventory outlining the type and quantity of components per unit area (eventually normalised to the total building cost of the given floor) for a specific building typology. Additionally, the assembled inventory is usually divided into distinct performance groups, with the components within each group being evaluated collectively. Consequently, it is essential that all components within a group are associated with the same EDP, typically peak interstorey drift (PSD) for drift-sensitive elements or peak floor acceleration (PFA) for acceleration-sensitive elements. In this study, the storey components were classified into five categories: 1. structural, 2. infills and partitions, 3. plumbing and electrical, 4. windows and doors and 5. other non-structural components.

iii. **Fragility functions:** Fragility functions for the building components (structural and non-structural) are selected to ensure their representativeness in relation to the specific characteristics of the building typology. Usually, only a single fragility model is considered per component. This study, however, uses multiple sources of fragility functions for a given component, with the goal of explicitly accounting for the epistemic uncertainty surrounding such models within the derived SLFs.

iv. **Repair costs:** Repair costs directly quantify the financial consequences of a seismic event and their accuracy allows for a more precise calculation of total losses. In a similar fashion to the fragility functions, different sources of repair costs were used herein to account for variability between construction practices and prices between distinct locations.

v. **Development of storey loss functions**: The last step estimates the storey loss functions for the defined component groups and conducts regression analysis to fit analytical formulations. The output of each loss function represents the total repair cost for the group components per unit area at different levels of EDP, assuming no collapse and no demolition of the building. Loss estimation follows FEMA P-58 guidelines, employing a probabilistic approach to assess damage and corresponding loss. Since multiple fragility and consequence functions were considered for the same component within a category, various fragility-consequence function combinations were developed for each component. Repair costs were then estimated using Monte Carlo simulation, where damage and loss were sampled for each individual component, and the total loss for the group was computed. The losses obtained from different combinations (within the same category) were merged, and regression analyses were performed on the full set of sampled repair costs.

3 APPLICATION TO PORTUGUESE BUILDINGS

3.1 RC building characteristics in Portugal

RC buildings comprise 51% of the total building stock in Portugal, accommodating 63% of the total population and occupying 63% of the total built area, as observed in the latest exposure model for Portugal [6]. According to multiple sources [7–9], RC buildings in Portugal can be divided into four main groups, concerning different periods of construction: (a) CDN – no seismic design, (b) CDL – low code; (c) CDM – moderate code and (d) CDH – high code. The first regulations with seismic provisions in Portugal were introduced in 1958 (RSCCS) [10] and 1961 (RSEP) [11], therefore, buildings built before 1960 were designed to withstand gravity loads only and belong to the CDN group. In 1983, an improved seismic design regulation (RSA 1983) [12] was introduced, thus, buildings built between 1960 and 1983 are defined as CDL and are the first generation of seismically designed buildings. CDM buildings are those built between 1981 and 2010, which marks the enforcement of EC8 in Portugal. The fourth and more recent typology buildings are CDH, which were constructed after 2011. It is noted that although the Eurocodes have been available in Portugal since 2010, EC8 only became the Portuguese enforced seismic code in 2019 [13]. Figure 1 illustrates the distribution of RC buildings, in terms of building count, population, and total reconstruction cost for each code level.

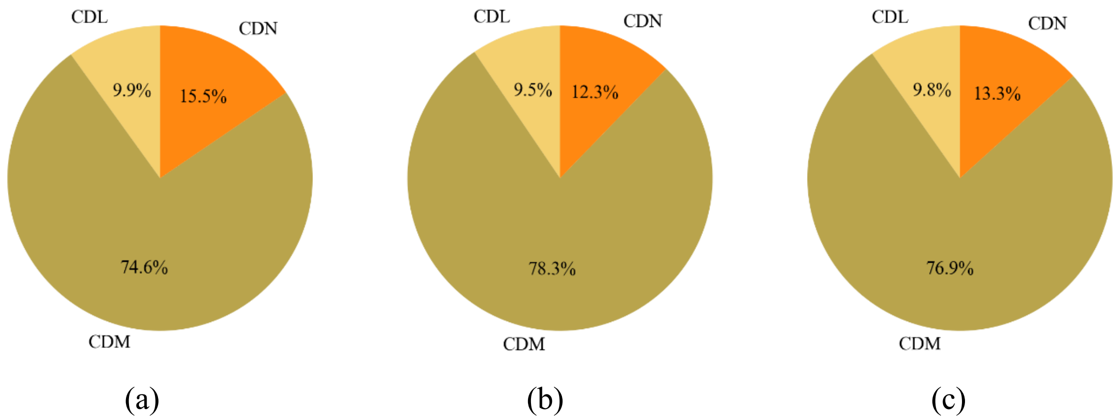


Figure 1: Distribution of RC buildings by code level in terms of a) building count, b) population and c) total reconstruction cost.

CDM buildings account for the majority in terms of building count, population, and total reconstruction cost. CDN and CDL buildings represent a smaller proportion, but are of particular concern regarding their seismic behaviour, primarily because they were designed with little to no consideration of seismic resistance needs. These buildings are predominantly moment-resisting frame structures, primarily designed to support gravity loads, and are often characterised by geometrical irregularities, slender RC elements, inadequate reinforcement in both quantity and detail, unconfined concrete with low compressive strength, insufficient cover, and smooth reinforcement rebars [7]. The majority of these buildings is characterised by the presence of masonry infill walls [9] that typically feature a cavity wall design, where the external leaf is thicker (usually 0.15 m) than the internal leaf (usually 0.11 m). The two layers of the wall were not connected, and the cavity between them was left empty [14]. Different studies have addressed the characteristics of reinforced concrete RC buildings in Portugal, focusing on various aspects such as buildings spatial distribution, period of construction and geometrical properties [8,9]. The following section outlines the methodology and data sources used in constructing storey loss functions tailored to these typologies of buildings.

3.2 Fragility functions

Given the lack of component-based fragility curves specifically derived to address the Portuguese building features, fragility functions from other studies were adopted, assuming that the component characteristics are similar. * The same fragility functions from Category 2 were used

Table 1 provides a summary of the fragility functions used in this study along with their EDP and respective sources.

Cat.	Components	Source	EDP
1	Interior beam-column joints	Cardone et al. [16], Pagni et and Lowes [18], Sengupta and Li [25]	PSD
	Exterior beam-column joints		PSD
	Brittle columns	Aslani and Miranda [15], Cardone et al. [16], Ruiz-García and Ramos-Cruz [17]	PSD
2	Infill walls	Cardone and Perrone [19], Chiozzi and Miranda [20], Rossi et al. [22], Sassun et al. [23], Del Gaudio et al. [26]	PSD
		Cardone and Perrone [19]	PFA
	Partitions	Aslani and Miranda [15], Cardone and Perrone [19], Rossi et al. [22], Retamales et al. [27]	PSD
3	Plumbing and electrical systems	*	PSD
		FEMA P-58 [1]	PFA
4	Windows and Doors	*	PSD
5	Under-floor cavity and floor undercoats	FEMA P-58 [1]	PFA
	Sanitary systems	[1]	
	Ceilings	[1,15,24]	

* The same fragility functions from Category 2 were used

Table 1: Fragility curves of the selected components of Portuguese RC buildings

Category 1 components, such as interior and exterior beam-column joints and brittle columns, are essential to the seismic performance of older moment-resisting RC frames. The adopted fragility functions were specifically chosen to address the common deficiencies present in existing gravity load-designed RC buildings in Portugal. These deficiencies include inadequate detailing of interior and exterior beam-column joints [15–17] and the presence of slender, short, and brittle columns with insufficient transverse reinforcement [16,18]. Regarding the infills and partitions (Category 2), both in-plane (IP) and out-of-plane (OOP) behaviours were addressed by incorporating PSD and PFA fragility functions, respectively. The fragility functions used for the masonry infill walls are based on clay hollow bricks, both with and without openings, which are considered representative of the typical Portuguese masonry infill walls [19–23]. Considering the specific construction typologies in Portugal, damage to plumbing and electrical systems (Category 3) is assumed to be correlated to the damage of masonry infills and partition walls (Category 2). Similarly, damage to windows and doors (Category 4) is assumed to be correlated to the failure of the infill walls. As a result, the fragility parameters assigned to these elements are considered identical to those of the infill walls, in line with the assumptions made in previous research studies [5,22]. Nevertheless, considering the possibility of plumbing and electrical systems being connected to the suspended ceilings, PFA fragility curves were also considered. Finally, for other non-structural elements (such as under-floor cavity and floor undercoats, sanitary fixtures, ceilings and stairs), the fragility functions from [1,15,24] were employed.

3.3 Consequence functions

Different sources of repair costs were considered to capture the variability arising from factors such as location and construction practices. Typically, when computing storey loss functions, it is necessary to input specific information about the quantities of the building components, which can be challenging when only general data is available. Using repair costs per square meter (€/m2) offers a more straightforward approach to estimate losses, as it enables loss calculations even in situations where detailed component data is uncertain or unavailable. In this study, different sources of consequence functions were used to account for the variability between repair activities and corresponding prices between different locations. The repair costs reported by Rossi et al. [22], based on the public works pricelist of Milan, were used to quantify the repair cost of infill walls and ceilings. Moreover, the study developed by Sassun et al. [23], based on the costing manual for the region of Rome, and both Del Gaudio et al. [26] and De Risi et al.[28], based on the price list for Public Works in the Abruzzo region, in Italy, were used to quantify the repair costs of masonry infills. Additionally, the consequence functions developed by Del Vecchio et al. [29] for different component categories, derived from actual repair cost data incurred for repairing RC residential buildings damaged by the 2009 L'Aquila earthquake, were employed. Table 2 presents the consequence functions used for different components, along with the corresponding price year per reference. To align the several fragility functions collected for each category, which have different damage states, with the selected consequence model, the damage states were carefully analysed and aligned to ensure consistency across both models. In cases where the damage states were not common to both fragility and consequence models, the consequence data were rescaled to match the fragility model, ensuring that each fragility state was associated with a corresponding consequence value.

Cat.	Source	DS1		DS2		DS3		DS4		DS5	
		μ	σ	μ	σ	μ	σ	μ	σ	μ	σ
1	Del Vecchio et al. [29]	1.7	3.1	4.1	6.1	8.5	20.7	6.6	9.5	10.3	24.3
2	Del Vecchio et al. [29]	34.5	35.5	91.3	47.9	108.3	73.4	125.4	61.8	122.0	37.5
	Saasun et al. [23]	59.7	4.4	139.3	4.4	186.7	63.9	186.7	63.9		
	Del Gaudio et al. [26]	73.0	3.9	101.3	4.0	270.1	15.3	328.7	44.6		
	De Risi et al. [28]	51.3		73.5		199.9					
	Rossi et al. [22]	56.0	0.0	151.7	18.1	160.1	17.6				
3	Del Vecchio et al. [29]	6.7	7.8	22.5	12.5	35.4	32.9	45.1	36.1	49.5	33.0
4	Del Vecchio et al. [29]	4.4	6.1	10.5	16.9	23.0	21.2	34.2	24.4	40.2	22.7
5	Del Vecchio et al.	14.3	8.8	21.2	17.7	39.0	30.9	50.9	43.1	68.8	27.1
	Rossi et al. [22]	3.2		19.4		32.3					

Table 2: Diverse consequence functions used for each component category and associated price year

3.4 Repair cost inflation and conversion factor

As mentioned in the previous section, different repair costs were retrieved from the literature, each associated with different reference years. To use these costs, the effect of inflation on was accounted for. All repair costs were adjusted considering the reference year 2022 and the inflation rates provided in Table 3.

2009	2011	2016	2017	2020
1.23	1.21	1.14	1.14	1.1

Table 3: Inflation rates from different years to the reference year (2022)

It is also necessary to account for differences in construction dynamics between the country from which the repair costs were obtained (reference country) and the target country. Various approaches exist to account for these differences, including adjustment factors based on labour costs, material prices and economic indices. In this study, the methodology proposed by Papadopoulos et al. [30] was adopted. This methodology calculates the repair cost conversion factor (RCCF) through Eq. 1. The reference country of the repair costs is Italy, while the target country is Portugal.

$$RCCF = \left(r_{lab} \cdot f_{lab}/r_{prod}\right) + \left(r_{mat} \cdot f_{mat}\right) + r_{m,p} \cdot f_{m,p} \tag{1}$$

In Eq. 1, f_{lab}, f_{mat}, and $f_{m,p}$ represent the proportion of the total repair cost associated with labour, materials, margins and preliminaries, respectively, in Italy. Meanwhile, r_{lab}, r_{mat} and $r_{m,p}$ denote estimated ratios of the costs of labour, material, and margins and preliminaries between Portugal and Italy. These parameters were obtained from national and international sources of data, such as Eurostat and Istat. Additionally, r_{prod} represents the difference in labour productivity between Portugal and Italy. It is calculated as labour productivity (c_{prod}), defined as the gross value added (GVA) of the construction sector per employed person, both sourced from Eurostat [31], multiplied by the average worker compensation [32]. The resulting RCCF indicates that the obtained repair costs should be adjusted by a factor of 0.62 for structural and architectural components (categories 1, 2, 3, and 4) and 0.66 for non-structural components (category 5). Table 4 summarizes the parameters employed to estimate the RCCF for different component types.

Component type	f_{lab}	f_{mat}	$f_{m,p}$	r_{lab}	r_{mat}	$r_{m,p}$	r_{prod}	RCCF
Structural and architectural	0.5	0.35	0.15	0.5	0.54	1.0	0.9	0.62
Non-structural	0.1	0.65	0.25					0.66

Table 4. Cost conversion parameters, taken for the year 2022

4 DERIVATION OF STOREY LOSS FUNCTIONS

The SLFs for various component groups were derived using a modified version of the toolbox provided by Shahnazaryan et al. [3], through regression analysis performed on the sample repair costs. Specifically, a Weibull cumulative distribution function (Eq. 2) was used to fit the data obtained by 200 Monte Carlo realisations. In Eq. 2, α, β and γ are the fitting coefficients, x is the EDP value, and y is the fitted loss ratio value.

$$y = \alpha\left(1 - e^{-\left(\frac{x}{\beta}\right)^{\gamma}}\right) \tag{2}$$

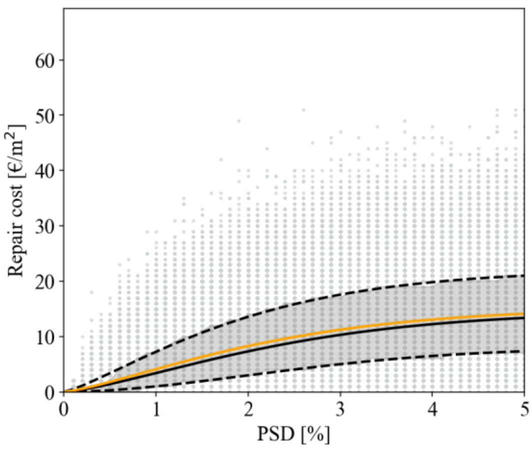
The goodness of the regression is then assessed by both the maximum relative regression error ($error_{max}$) (Eq. 3) and the cumulative relative regression error ($error_{cum}$) (Eq. 4) across the entire EDP range, for each component performance group. The maximum relative error captures the largest discrepancy between the predicted and observed loss values, offering a measure of the worst-case deviation. In turn, the cumulative relative error aggregates the overall fitting discrepancies across the full range of EDP values, providing a more comprehensive evaluation of the regression performance. In Eq. 2 and Eq. 3, the terms C_{repair}^{EDP} and $\widehat{C}_{repair}^{EDP}$ correspond, respectively, to the original and fitted repair costs.

$$error_{max} = max\left(\frac{\left|C_{repair}^{EDP} - \widehat{C}_{repair}^{EDP}\right|}{max\left(C_{repair}^{EDP}\right)}\right) \tag{3}$$

$$\begin{aligned} error_{cum} &= \int_{0}^{EDP=\max EDP} error_{max}\ dEDP \\ &= \int_{0}^{EDP=\max EDP} max\left(\frac{\left|C_{repair}^{EDP} - \widehat{C}_{repair}^{EDP}\right|}{max\left(C_{repair}^{EDP}\right)}\right) dEDP \end{aligned} \tag{4}$$

Figure 2 illustrates the SLFs obtained for various component categories, including the 16th, 50th, and 84th percentiles. The scattered data points corresponding to each realisation are also shown, highlighting the significant variability in repair costs within the same component category. Table 5 summarises the fitting coefficients of the Weibull distribution for all the component categories, while Table 6 presents the goodness of the regression parameters used to evaluate the performance of the SLFs. The obtained SLFs show that the maximum and cumulative relative regression errors across the EDP range for all component categories remain consistently below 11% and 2%, respectively.

Structural components



Infills and partitions

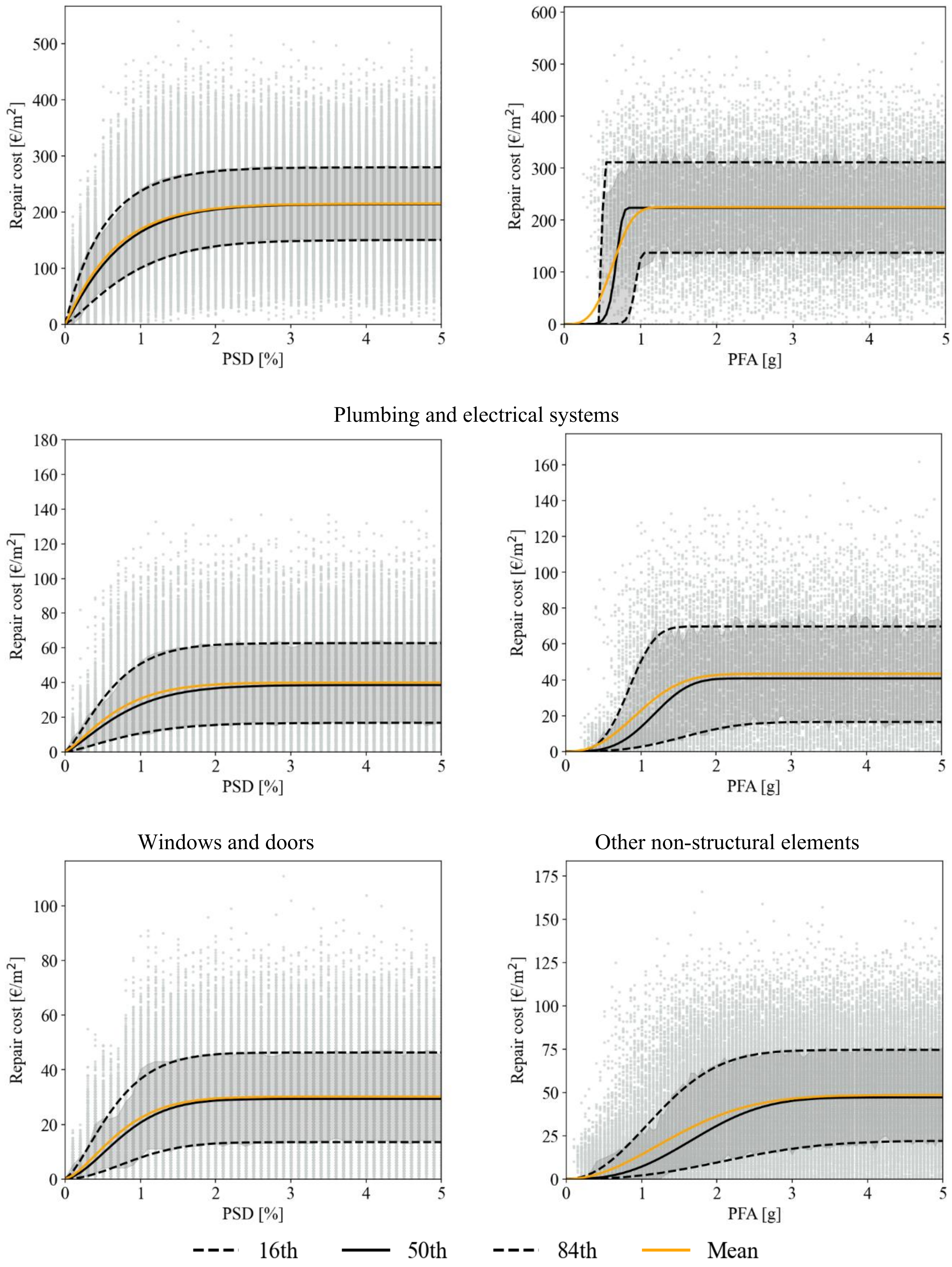


Figure 2: Proposed storey-loss functions (SLFs) for other non-structural elements

Cat.		**1**	**2**		**3**		**4**	**5**
EDP		PSD	PSD	PFA	PSD	PFA	PSD	PFA
	α	1.001	0.975	0.854	0.930	0.714	0.902	0.853
16th	β	0.031	0.009	0.985	0.010	1.680	0.011	2.509
	γ	1.826	1.241	11.462	1.390	3.139	1.989	2.520
	α	0.968	0.987	0.898	0.941	0.854	0.947	0.943
50th	β	0.025	0.007	0.708	0.009	1.266	0.009	1.960
	γ	1.390	1.096	13.436	1.304	3.506	1.629	2.686
	α	0.959	0.985	0.928	0.965	0.904	0.966	0.956
84th	β	0.020	0.005	0.540	0.007	0.926	0.007	1.428
	γ	1.251	0.969	4.858	1.320	3.445	1.383	2.136
	α	0.986	0.990	0.921	0.972	0.896	0.969	0.956
Mean	β	0.024	0.007	0.715	0.008	1.103	0.008	1.705
	γ	1.320	1.043	3.545	1.246	2.477	1.470	2.001

Table 5: Summary of the fitting coefficients of the Weibull distribution for all the component categories

Cat.	**1**	**2**		**3**		**4**	**5**
EDP	PSD	PSD	PFA	PSD	PFA	PSD	PFA
$error_{max}$	4.27%	2.59%	7.87%	3.79	10.55%	10.41%	4.36%
$error_{cum}$	0.11%	0.09%	0.79%	0.21%	1.31%	0.27%	0.58%

Table 6: Goodness of the regression parameters

5 CONCLUSIONS

This study developed storey loss functions (SLFs) tailored specifically to Portuguese RC buildings, constructed before 1980, focusing on critical components like beam-column joints, brittle columns, masonry infills, and non-structural elements such as plumbing, electrical systems, windows and doors. These buildings, which are either without seismic design or designed according to low seismic design provisions, often suffer from deficiencies such as insufficient reinforcement, geometric irregularities, and a lack of seismic design considerations. Given the lack of studies addressing component-based fragility curves and corresponding consequence functions specifically derived to address the Portuguese building features, studies from other countries were adopted, assuming that the component characteristics are similar. The consequence functions selected for the SLF development were adjusted for inflation and construction dynamics between Portugal and Italy, taken as country of reference, ensuring the applicability of the repair cost data to the Portuguese context. Different sources of fragility curves and repair costs were used from available literature to capture the variability in construction practices, geographic location, and building typologies, and to explicitly account for the epistemic uncertainty surrounding the generated SLFs. The proposed SLFs offer a valuable tool for estimating the economic loss of RC buildings in Portugal, providing practical tools for policymakers, engineers, and researchers to assess and mitigate the risks posed by earthquakes.

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