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ENHANCING FUNCTIONAL RECOVERY ESTIMATIONS THROUGH STOREY LOSS FUNCTIONS

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Abstract

The computationally intensive nature of performance-based earthquake engineering (PBEE), particularly when implemented through detailed component-based approaches such as FEMA P-58, has limited its use primarily to academic research and specific studies. A more streamlined alternative, favoured by practitioners, employs storey loss functions (SLFs) to estimate expected monetary loss per storey based on seismic demand. This method significantly reduces the data required for analysis, which is particularly beneficial during the design phase when detailed component information may still be unavailable. This paper presents a customisable, user interface (UI)-based tool for use in the seismic design and assessment of buildings. Unlike the FEMA P-58 methodology, which assumes full recovery, where every damaged component must be repaired before the building is considered functional, recent studies have shown that occupants and building managers exhibit varying degrees of tolerance based on the situation. The proposed tool addresses this by targeting specific recovery states (RSs), including functionality recovery, re-occupancy, and full recovery, allowing for a more detailed disaggregation of losses in particular associated with non-structural elements. To make economic loss estimates more reflective of real-world conditions, the concept of RS should be incorporated, and the anticipated RS should be explicitly stated when conducting a loss assessment. This approach provides decision-makers with a more rational and informed strategy for estimating recovery times at different stages of the process.

Keywords: storey loss functions, recovery stages, losses, functional recovery.

1. Introduction

The introduction of the Pacific Earthquake Engineering Research (PEER) Centre's performance-based earthquake engineering (PBEE) framework [1] has enabled seismic engineers to assess damage to various building components in a more probabilistic manner. Building on this, the FEMA P-58 guidelines [2] allow users to translate expected damage into estimates of repair costs, downtime, and potential loss of life in buildings after an earthquake. This approach has gained significant traction in recent years, with numerous studies emphasising the substantial contribution of non-structural elements (NSEs) to monetary losses. Over the past 20 years, engineers have increasingly recognised that using decision variables like monetary loss is a more effective way to convey seismic risk to clients and stakeholders. However, applying a methodology like FEMA P-58 involves making critical assumptions about factors such as seismic hazards and structural modelling.

A simplified alternative to PEER's building-specific loss estimation was proposed by Ramirez and Miranda [3]. This approach introduced engineering demand parameter versus decision variable (EDP–DV) functions, which directly link structural response parameters (EDPs) to economic losses (DVs). These functions, referred to here as storey loss functions (SLFs), typically estimate monetary losses at the building storey level. By offering predefined loss functions that describe repair costs for a generalised inventory of damageable components, SLFs significantly reduce computational complexity and the data requirements for a building's inventory during loss estimation. This simplification is particularly beneficial during the design phase, when detailed information about building components is often unavailable. Generic SLFs help address this limitation by reducing the excessive computational effort associated with component-based approaches. Recent applications of SLFs include their

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implementation by Silva et al. [4] for steel buildings and Shahnazaryan et al. [5] for reinforced concrete buildings in a European context. Significant research has been undertaken to support the development of EDP–DV functions and loss assessment methodologies, focusing on creating fragility and consequence functions for a variety of structural and non-structural components (e.g. [6]–[11]). Perrone et al. [12], for example, introduced a method for estimating the expected annual loss (EAL) of Italian reinforced concrete buildings, which incorporates appropriate SLFs. This further emphasises the necessity of advancing simplified approaches to streamline loss estimation processes.

The objective of this paper is to explore the consideration of level of recovery expected by building managers following post-earthquake repairs and how it impacts the expected losses. Specifically, it investigates whether buildings are expected to be fully restored to their pre-earthquake condition, potentially with improvements, or whether a lower level of repair would be deemed acceptable in the short to medium term. This topic was chosen for detailed exploration due to the valuable insights gained from recent earthquakes in Japan [13],which were informed by structural health monitoring (SHM) data, damage reports, and interviews with commercial building managers and owners. To facilitate this investigation, a toolbox featuring a graphical user interface (UI) is introduced here. This toolbox enables the automated generation of SLFs through regression analysis and accommodates different recovery states (RSs), as escribed in the methodology outlined by Molina Hutt et al. [14], offering a more accurate reflection of real-world conditions.

2. Storey loss function generation tool

The framework incorporated within the toolbox is detailed in this section, as initially presented in Shahnazaryan et al. [5]. Key decisions to be made prior to using the toolbox include characterising the building by defining the component inventory, which is determined by the quantities, fragility, and consequence functions of the components. Additional considerations involve performance grouping of components based on their sensitivity to EDPs, identifying potential interactions between different components, selecting the number of simulations for sampling damage states (DSs), and choosing the type of regression fitting for the analysis. The framework consists of several steps and is depicted in Figure 1.

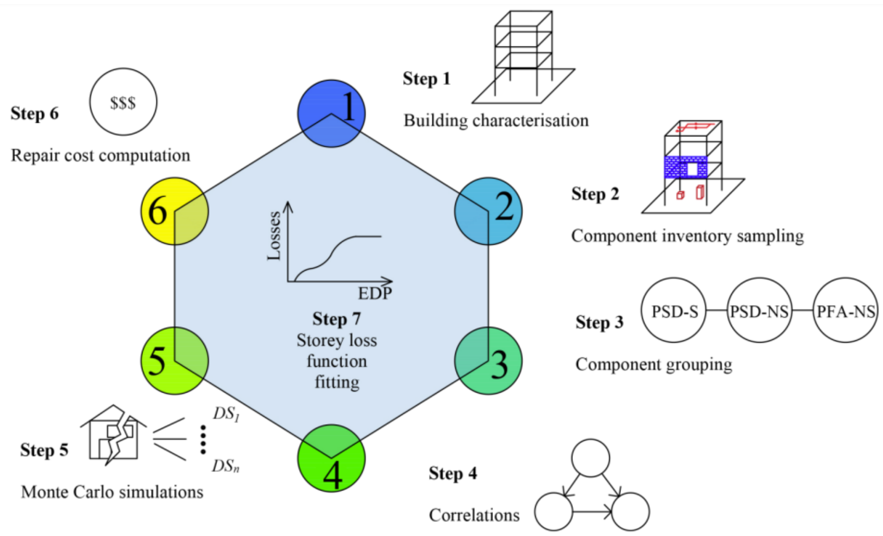

Figure 1. Storey loss function generation framework.

The process starts by identifying the building's characteristics, such as storey count, dimensions, occupancy, and usage. If these are unknown, SLFs can be based on a reference area and adjusted for the building's actual size (e.g., [12], [15]). Once the characteristics are determined, a damageable component inventory is created, considering structural and non-structural components, as well as contents likely to be damaged. The component inventory includes item types, quantities, EDP sensitivity, and whether the component is structural or non-structural. Components are grouped into

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three performance categories, and fragility and consequence functions should be provided, often adapted from sources like the FEMA P-58 database [16]. To apply the framework to 3D buildings, it must be used separately for each direction, with components oriented along those directions. Components can then be grouped and analysed using structural and non-structural demands in the two orthogonal directions. However, interactions between seismic effects in orthogonal directions are not accounted for, and if such interactions are significant, more advanced loss assessment methods should be used but for most practical applications it is sufficient. Once the component inventory is defined, components are classified into groups based on their type (structural or non-structural) and EDP (e.g., peak storey drift (PSD) or peak floor acceleration (PFA)). Components within each performance group are assessed together, with their mutual demand leading to the calculation of the group's SLF. In essence, losses from all components in a performance group are linked to the same EDP. Classifying components into performance groups, alongside separating different component typologies, enables the disaggregation of losses at later stages to identify the key contributors to economic losses, as recently discussed in O'Reilly and Shahnazaryan [17]. This is particularly useful for visualisation, as it allows for easy identification of key loss contributions from collapsing and non-collapsing cases, as well as from individual storeys and performance groups (e.g., structural and non-structural components).

Similar to the studies by Ramirez and Miranda [3], structural and non-structural components sensitive to the same EDP can be grouped to account for potential correlations between their damage states. For instance, a specific intensity level may not directly damage a non-structural component, but it could affect another connected component that does sustain damage. In such cases, repair of the damaged component may require access, which could involve removing part or all of the undamaged non-structural component. Following Monte Carlo simulations and repair cost computations, regression is performed to identify the fitted SLFs.

Figure 2 and Figure 3 display the tool, which features an intuitive graphical UI designed to simplify the creation of SLFs for seismic assessment. Below is a description of the key elements and functionality of the tool's use.

1. **Main dashboard:** allows for the upload and download of inputs and outputs.
2. **Inventory:** where element inventory is defined in a table format. The users are able to perform create, read, update, and delete (CRUD) operations. Here, non-structural, structural elements or content is defined along with their quantities and EDP-sensitivity. The elements may be further categorised into different groups.
3. **Advanced:** element correlation matrix may be set dynamically depending on the updates associated with the element inventory. Additionally further calculation details may be adjusted, such as: number of Monte Carlo simulations, regression functions to be used (as of writing this paper, it supports Weibull [18] and Papadopoulos et al. [15]), and other parameters associated with visualisations.
4. **Visualisations:** allows the users to visualise the SLFs for each performance group, along with error metrics and fitting parameters.

The tool is available here: https://apps.djura.it/structure/edp-dv/standard.

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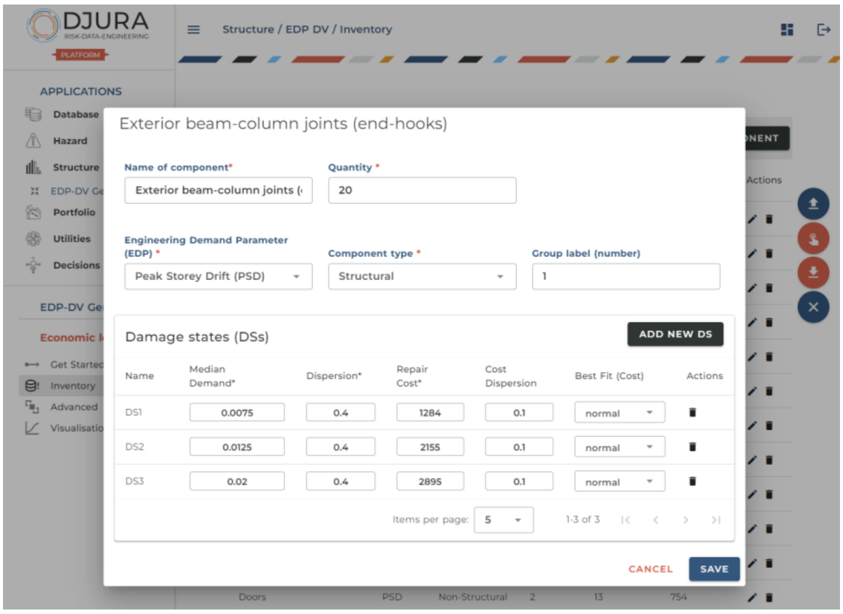

Figure 2. Overview of the graphical UI of the SLF generator.

Figure 3. Sample SLF visualisation.

3. Relative importance of NSEs for functional recovery

In recent decades, seismic engineers have increasingly recognised the importance of NSEs in overall building performance. This understanding traces back to observations made by Engle [19] in the 1920s, who highlighted that a building with significant NSE damage, such as partitions and finishes, is largely unusable after an earthquake, even if the structural frame remains intact. This was later reiterated and popularised by Taghavi and Miranda [20], who examined the monetary investments required for office, hotel, and hospital buildings, breaking them down into structural, non-structural, and building contents contributions. This straightforward illustration (Figure 4) reinforced Engle's earlier points and laid the groundwork for a more integrated approach to evaluating the impacts of NSEs on building performance. Similar findings have also been reported by Dhakal et al. [21] in recent years in New Zealand.

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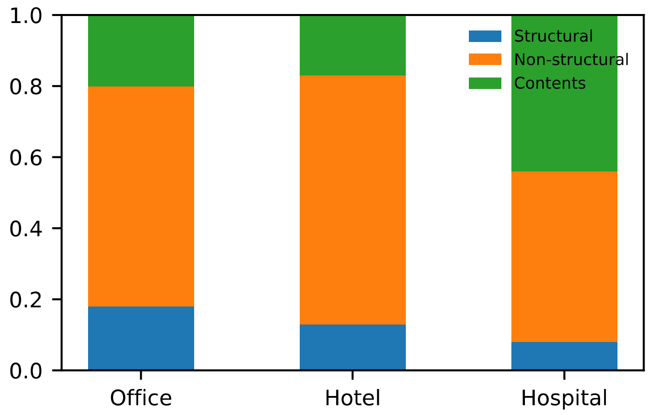

Figure 4. Cost breakdown of typical buildings in the US.

The significant role of NSEs in a building's financial investment was further illustrated by O'Reilly et al. [22], who examined the repair costs needed to fully rehabilitate a school building under increasing levels of ground shaking. The data, developed from surveys and instrumentation of an existing school building in central Italy, is shown in Figure 5 (left), where NSEs clearly dominate the percentage contributions to economic losses up until a return period of around 900 years, at which point their contribution drops to approximately 60%. While Figure 5 (right) demonstrates the importance of NSEs, with their relative contribution to EAL being over 45%.

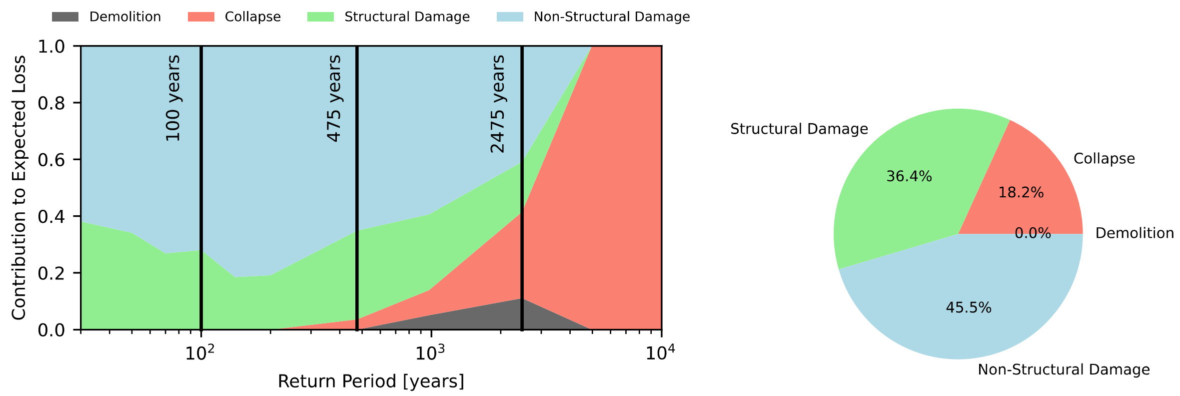

Figure 5. Relative contribution to (left) the expected loss versus return period of ground shaking and (right) to the EAL.

The recent Japanese earthquakes are focused on, specifically the 2018 Osaka and 2018 Hokkaido Eastern Iburi events, to compare research conclusions with actual observations following strong shaking. Data on structural and non-structural damage were collected through the q-NAVI system [23], which is an SHM system deployed in over 500 buildings (as of 2021) in various parts of Japan. Additionally, interviews and reports on the impacts to building functionality were invaluable. These observations focused on commercial buildings with typical office-type NSEs, which is significant because such buildings are usually owned by a single entity responsible for decision-making. This contrasts with residential buildings, where individual units are often owned separately, complicating decision-making for the building as a whole. The q-NAVI system reported no significant structural damage during the 2018 Osaka earthquake, but numerous buildings experienced damage to their NSEs. These included cracks in gypsum partition walls, water leaks from pipes, collapsed tiles from suspended ceiling systems, and the failure of some mechanical devices, representing various NSE types (e.g., drift vs. acceleration sensitive, fixtures vs. mechanical services). Despite the noticeable NSE damage, building maintenance managers, both on-site and at headquarters, along with the building owners,

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concluded that the damage was not critical. They found that in many cases, the damage to NSEs was tolerable for both short- and long-term operations, preventing panic over high repair costs and financial losses often predicted in analytical studies. Many NSEs had relatively minor damage, and when strictly following the FEMA P-58 framework [2], their repair cost implications can be significant.

After the earthquake, partitions often needed full replacement throughout the building, along with repainting and redecorating—processes likely to be expensive and disruptive, especially given the post-earthquake scarcity of materials and labour. Initially, the damage appeared alarming to occupants, but within a few days, it became less concerning. Many occupants regarded the damage as a minor inconvenience, even likening it to an amusing addition to their surroundings. This shift in perception was driven by a desire to clean up and perform quick, ad hoc repairs to return to normal operations once the building was deemed safe. In Japan, this composed response can largely be attributed to effective earthquake safety education, awareness programmes, and frequent earthquake exposure. However, such behaviour may vary significantly in other countries due to differences in preparedness, information dissemination, and experience with seismic events. In some cases, building managers expressed concerns about NSE damage affecting the building's post-earthquake functionality. These issues primarily involved water-related damage, failures in essential mechanical services, and the dislocation or partial collapse of exterior cladding tiles. Water-related damage, such as burst pipes, led to flooding in specific areas, making it impossible for occupants to address the issue immediately. Instead, it required the replacement of damaged items, furnishings, and the piping system itself.

Given those observations in the data collected in Japan regarding the actual impact of NSEs, representation of NSE repair costs in analytical formulation may be an overstatement. Studies like Bonowitz [24] defined RSs as benchmarks for building recovery, including re-occupancy, functional recovery, or full recovery, each representing a compromise on complete restoration. To enhance downtime estimation and model the building recovery process, the REDi rating system by Almufti and Willford [25] introduced the concept that regaining functionality requires a sequence of key repair actions to gradually restore a building to a portion of its original functionality. Molina Hutt et al. [14] expanded on RS concepts with TREADS, defining five RSs ranging from "full recovery" to "stability," as outlined in Table 1.

Table 1. Recovery states by different building recovery frameworks

Recovery state	FEMA P-58	REDi	Molina Hutt et al. [14]
Full recovery (RS1)	x	x	x
Functional recovery (RS2)		x	x
Re-occupancy (RS3)		x	x
Shelter-in-place (RS4)			x
Stability (RS5)			x

To make economic loss estimates more realistic and in line with these observations following major earthquakes around the world, RSs should be integrated into loss assessments, with the targeted RS explicitly stated, and not implicitly assumed to be full recovery (RS1). This involves scrutinising the damageable inventory to determine which components are essential for achieving a specific RS. Each component's DS must be evaluated to decide its impact on the targeted RS. For instance, minor partition wall damage observed in Japan might not hinder "functional recovery" and could be excluded from the loss assessment. In contrast, damaged water pipes would directly affect functionality and must be included in the evaluation. This approach effectively narrows the damageable inventory to only what is essential for the desired RS.

4. Case study application

This case study analyses a four-storey reinforced concrete frame structure previously analysed by Shahnazaryan et al. [26] and designed according to Eurocode 8 provisions [27] for a site in L'Aquila,

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Italy. The structure utilised concrete with a compressive strength of 25 MPa and steel with a yield strength of 415 MPa. It was designed as a regular structure, free of plan or elevation irregularities. The structure was modelled in OpenSees [28] as a single planar frame for simplicity, with floor masses lumped and nodes constrained horizontally to replicate rigid diaphragm behaviour. Nonlinear behaviour in beams and columns was represented using a concentrated plasticity approach, while elastic sections were assigned cracked section stiffness. Beam-column joints were treated as rigid, and capacity design principles ensured no shear mechanisms were included in the model. To characterise non-linear performance, the backbone curves for each structural element were derived from moment-curvature relationships. Plastic hinge lengths were calculated following Priestley et al. [29]. Vertical gravity loads were applied to a leaning column to account for P-Delta effects during nonlinear analysis. Additionally, Rayleigh damping corresponding to 5% of critical damping was implemented. The column bases were modelled as fixed supports to simplify boundary conditions.

Incremental dynamic analysis [30] was performed and losses were calculated using the storey loss function approach as outlined by Shahnazaryan et al. [5]. For the damageable inventory and the specific details regarding component quantities, repair costs, and fragility functions refer to the original study as they are not directly pertinent to the current discussion. To integrate the RS outlined in Table 1, each DS of the components were mapped to a corresponding RS. If a DS occurs, the building cannot be considered within that RS until repairs are completed. For instance, the most severe DS of structural elements, involving rebar fracturing and concrete spalling, was linked to 'stability' (RS5), as this condition would compromise the building's structural stability. Similarly, the first two DSs of internal partitions were tied to 'full recovery' (RS1), as their light damage can be tolerated in other RSs but not when full recovery is required. During loss assessments, only the DSs relevant to the targeted RS were included. For instance, targeting 'full recovery' necessitates considering all DSs linked to RS1 or higher. Conversely, targeting 'functional recovery' would involve DSs linked to RS2 or higher, excluding DSs tied to less severe damage. This approach allows decision-makers to focus on specific damage scenarios and exclude tolerable DSs, refining the loss estimate according to recovery priorities.

The results of loss assessment are shown in Figure 6. When evaluating the 'full recovery' state, as commonly assumed in guidelines like FEMA P-58 [2] and in previous studies like O'Reilly et al. [22], the EAL was calculated as 1.42%, with the majority of costs being attributed to repairing NSEs. Although exact EAL varies depending on the specific structure, site conditions, and inventory composition, the result aligns with prior research emphasising the significant role NSEs play in overall losses. However, when the damageable inventory was adjusted to include only the essential repairs for achieving less stringent recovery states, such as 'functional recovery' or 're-occupancy,' the EAL dropped significantly to 0.83% and 0.58%, respectively. This represents a reduction of 42% and 60%, primarily because repairs to non-essential NSEs were excluded, reflecting the more flexible approach seen in Japan, where certain damage could be tolerated without impacting the building's functionality.

The case study and discussions highlight an improved method for assessing losses, moving beyond the assumption of 'full recovery.' This refined approach offers decision-makers a clearer picture of the expected RS for a given EAL value, along with insights into the primary contributors to the EAL. This approach helps avoid unnecessary focus on non-essential components during retrofitting, preventing the waste of financial resources on repairs that may not be required.

The overarching focus remains on life safety, ensuring a sufficient margin against structural failure while also addressing direct economic losses. This approach is particularly relevant for commercial buildings with centralised ownership, which can prioritise essential repairs over non-critical ones. In contrast, in residential buildings, where ownership is fragmented, coordinating such decisions may be more challenging. Adopting a more measured approach, such as delaying repairs until post-disaster demand and prices have subsided, could help reduce costs. This strategy mirrors the decision-making in Japan, where minor NSE repairs were deferred until the next scheduled refurbishment, avoiding the inflated costs of immediate post-earthquake repairs.

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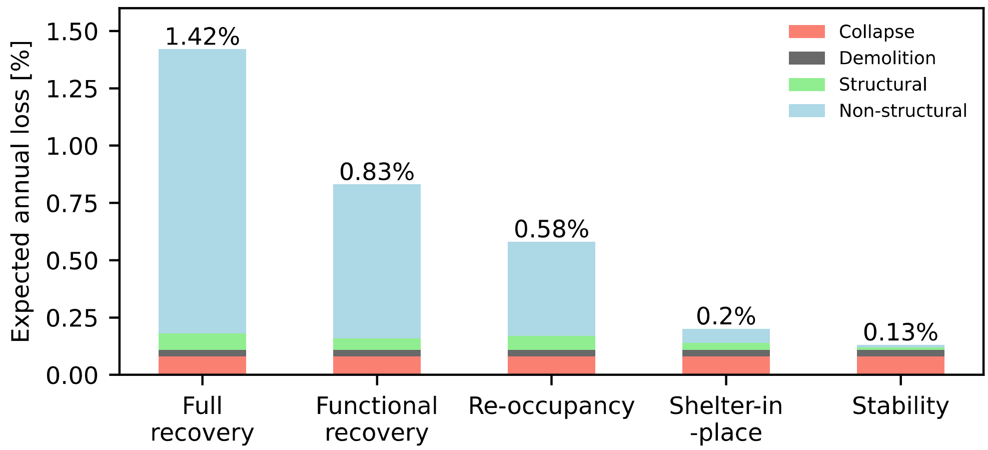

Figure 6. EAL results as a function of RS targeted.

5. Summary

This paper presented a practical tool for preparation of storey loss functions (SLFs) that uses a graphical user interface for ease of its application. This tool allows users to input specific building parameters and assess which components contribute most to economic losses, offering a detailed view of what repairs are necessary for achieving the desired recovery state. Using the presented tool key issues related to estimating damage to non-structural elements (NSEs) in earthquakes were addressed, along with the broader performance implications. Drawing on observations from commercial buildings affected by recent earthquakes in Japan, it offers valuable insights into the realities faced by building managers and owners, contrasting these with recent advancements in research. The findings from Japan underscore a practical approach to earthquake recovery, where functional recovery, rather than full recovery, is often deemed sufficient.

Analysis of interviews with commercial building owners and managers after recent Japanese earthquakes revealed that, in many instances, minor damage to NSEs was not immediately critical, particularly in the context of price and demand surges following major seismic events. This finding contrasts with existing literature, which stresses the significant role of NSEs in the economic impacts of earthquakes, including initial investment costs and potential financial losses, while emphasising the need for improved NSE performance to enhance overall resilience. However, what was considered critical in these cases were issues that directly affected the building's usability, particularly water damage from burst pipes.

These observations align with what is commonly referred to as "functional recovery" in the field, marking a shift from the traditional focus on full recovery to more practical, lower levels of recovery that still meet the needs of building owners and decision-makers. A case study was provided to show how this concept could be incorporated into loss assessments. The key takeaway from this analysis is that by prioritising functional recovery or re-occupancy instead of full recovery, the expected annual losses could be reduced by 42%–60%, as repairs to NSEs deemed non-essential could be postponed. This suggests that a more thoughtful evaluation of the relative importance of various building components should be incorporated into repair and retrofitting decisions, with the anticipated recovery level clearly defined in advance.

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