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Towards the assessment and risk classification of existing building typologies using storey-loss functions

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ABSTRACT: Seismic loss assessment is becoming a common instrument in the assessment of existing structures. Different approaches exist, with varying degrees of complexity and level of detail, but despite these developments in research, there remains a necessity to provide practitioners and decision-makers with simplified tools for building-specific loss assessment. A simplified alternative to computationally expensive loss assessment calculations is storey-loss functions (SLF). These reduce the computational effort by providing pre-calibrated loss functions describing the repair costs of a predefined building inventory of damageable components of a particular building typology of interest in a simplified manner. Direct economic losses can be estimated with respect to structural response parameters, such as storey drifts and peak floor accelerations. To this end, this paper presents a loss-assessment framework, employing generalized pre-calibrated SLFs tailored for infilled reinforced concrete structures with damageable inventory, particularly of the construction practice in Southern Europe. A case study application is presented where findings of both, extensive and simplified analyses are presented and compared to illustrate the relative accuracy and applicability of the method.

1. INTRODUCTION

Loss assessment is becoming a more common instrument in the seismic performance assessment of existing structures. Different approaches exist with varying degrees of complexity. The most notable is the component-based approach implemented within the FEMA P-58 guidelines (Applied Technology Council (ATC) 2012). However, despite the latest research developments, there remains a need to provide practitioners with tools to conduct a building-specific loss assessment in a simple but accurate manner. A simplified alternative to computationally intensive loss assessment via storey-loss functions (SLFs) (Ramirez and Miranda 2009). SLFs define the expected repair costs at a storey level with a defined inventory of damageable components thus reducing the computational effort through a pre-calibrated relationship between the engineering demand parameters (EDPs) and expected repair costs.

The Italian *Sismabonus* framework is outlined in detail by Cosenza et al. (2018) and utilizes the data on repair costs collected following the L'Aquila earthquake (Dolce and Manfredi 2015). *Sismabonus* was subsequently integrated within the Italian building code (NTC2018) to provide practitioners with a simple framework to assess the overall performance of buildings and qualitatively illustrate the beneficial improvement following retrofitting interventions. Despite the several benefits of implementing such an accessible and straightforward framework, recent studies (Nafeh and O'Reilly 2022a; O'Reilly et al. 2018) have shown that it possesses limitations with respect to more rigorous risk and loss analyses.

To this end, this study presents a generalized storey-loss function approach for the direct estimation of economic losses induced during seismic shaking intended for practical application and tailored for the infilled reinforced concrete (RC) building typology. The estimation of direct losses utilises pre-calibrated SLFs for the infilled RC typology with EDPs like peak storey drifts (PSD) and peak floor accelerations (PFA). The accuracy of the SLF-based approach is appraised via a case study comparison with other rigorous (i.e. component-based approach outlined by FEMA P-58 (Applied Technology Council (ATC) 2012) and simplified (i.e. *Sismabonus*) loss assessment methodologies.

2. OVERVIEW OF SEISMIC LOSS ASSESSMENT METHODOLOGIES

The FEMA P-58 component-based approach is a rigorous procedure which requires a full building inventory along with fragility and consequence functions at the component level to be defined. As such, the damage information from damageable inventory (i.e. structural and non-structural components) is converted to decision variables (DVs) . The DVs are more commonly referred to as “deaths, dollars and downtime” as highlighted within the PEER framework (Cornell and Krawinkler 2000). The FEMA P-58 methodology first requires that a probabilistic quantification of structural performance through adequate EDPs (e.g. PSDs and PFAs) be carried out. This is generally the outcome of extensive nonlinear time-history analyses (NLTHA) such as incremental dynamic analysis or multiple stripe analysis (MSA). Additionally, this step requires that a case study building is accurately modelled accounting for the formation of all possible inelastic mechanisms and the selection of a suitable ground-motion set for the characterization of the structural response up to collapse. The interface between structural response and a given ground motion intensity is typically defined through fragility functions. Then, the identification of damageable structural and non-structural components inventory and in terms of component quantities, associated repair costs, fragility and consequence functions is required. For practical implementation, such information is included in the electronic Performance Assessment Calculation Tool (PACT) for carrying out probabilistic calculations and assessment of losses.

Furthermore, the Italian standards for the risk classification of buildings or *Sismabonus* introduced a set of guidelines for the seismic assessment of structures. The technical principles aim to characterise simplistically the structural capacity, through what is known as the “life-safety index” and seismic losses via the expected annual losses (EAL). These technical principles aim at providing practitioners with simplified tools and incentivising the general public to perform seismic strengthening interventions on an existing building in the form of tax deductions. The approach is quite simple as it requires the analyst to conduct just a pushover analysis and eliminates the need for many of the steps involved in the PEER-PBEE loss estimation methodology described in FEMA P-58, for example. The result of the guidelines is that an EAL value is computed and classified within a letter-based system similar to that initially proposed by Calvi *et al.* (2014). To do this, the Italian guidelines first highlight that the practitioner must evaluate the building capacity expressed in terms of the annual frequency at five different limit states (LS). These limit states are namely the initial damage, operational, damage limitation, life-safety, collapse and reconstruction. To determine the mean annual frequencies at each limit state (MAFE) λ, a simplistic formulation is proposed where a correlation between the limit states is used. Once the MAFE is computed, fixed values of the repair costs associated with the aforementioned limit states and expressed as a percentage of the replacement cost ($\%R_C$) are considered. Consequently, these repair costs are used to determine the λ -$\%R_C$ relationship. Finally, EAL is evaluated as the area under the λ-

$\%R_C$ relationship which can be subsequently calculated as such:

$$EAL = \sum_{i=2}^{5} [\lambda(LS_{i-1}) - \lambda(LS_i)] * \frac{[\%R_C(LS_i) - \%R_C(LS_{i-1})]}{2} + \lambda(CLS) * \%R_C(RLS) \tag{1}$$

where the index i represents the considered limit state, and i=1 and i=5 correspond to IDLS and CLS, respectively.

Considering the SLF-based approach, the proposed assessment methodology is illustrated in Figure 1. First, a hazard analysis at the location of interest should be carried out where the hazard is expressed in terms of the MAFE of a selected range of intensity measure levels. Second, a detailed numerical model of the case study structure is needed to perform NLTHA at each chosen intensity measure level (IML) for the subsequent characterization of the structural response. This step concludes with the derivation of PFA and PSD profiles at each storey for each considered IML. Third, using the proposed generalized storey-loss functions, an interpolation for the expected loss ratio corresponding to each storey at each IML is carried out, for the structural and non-structural components losses. Then, the seismic risk associated with each IML is derived as a function of the MAFE. Finally, the EAL value is calculated, integrating under the MAFE-Loss Ratio curve.

For the derivation of a set of generalized SLFs, the required steps are illustrated in Figure 2. First, a storey typology should be considered (e.g. ground floor infilled). Second, an adequate characterization of the storey typology should be carried out. This refers to the proper identification of information related to occupancy type, structural system and other architectural features. Following such characterization, a comprehensive consideration of the damageable component distribution is needed. The component inventory was split into three principal performance groups (PGs): drift-sensitive structural components, drift-sensitive non-structural components and acceleration-sensitive non-structural components.

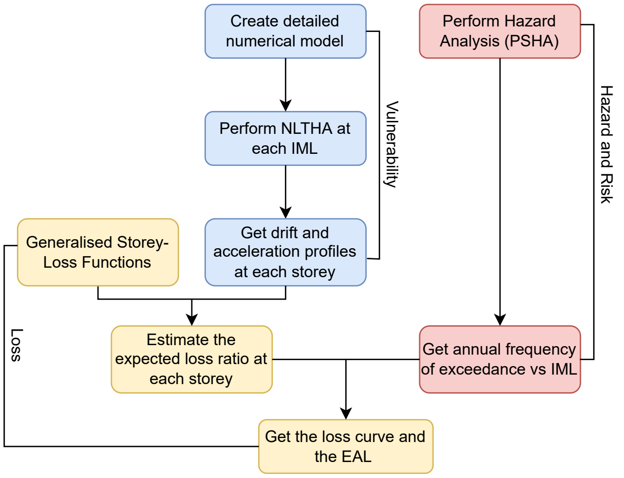


Figure 1: Summary of the proposed SLF-Based approach for the loss estimation of infilled RC frame structures

To this end, a database of archetype buildings previously developed in recent studies (Nafeh and O'Reilly 2022b; O'Reilly and Nafeh 2021) has been utilised. These infilled RC building archetypes were conceptualised and designed through simulation of the design procedures in force over various periods to incorporate the seismic performance characteristics and the anticipated damageable inventory of this typology typically found in Italy. The architectural considerations highlighted herein do not just reflect the archetype design space adopted but provide information on the building's structural and non-structural component inventory which are key elements in loss assessment. Once the components are defined, all relevant information such as fragility and consequence functions were obtained. The generalized SLFs were derived using the Python toolbox developed by Shahnazaryan *et al.* (2021), available at: https://github.com/davitshahnazaryan3/SLFGenerator.

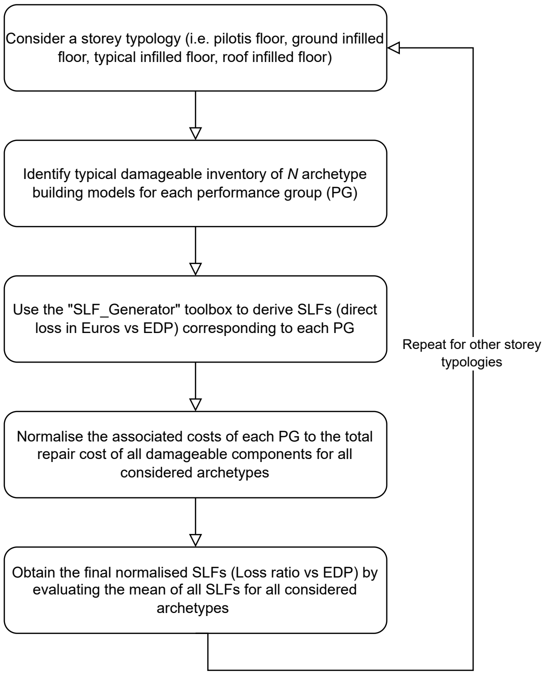
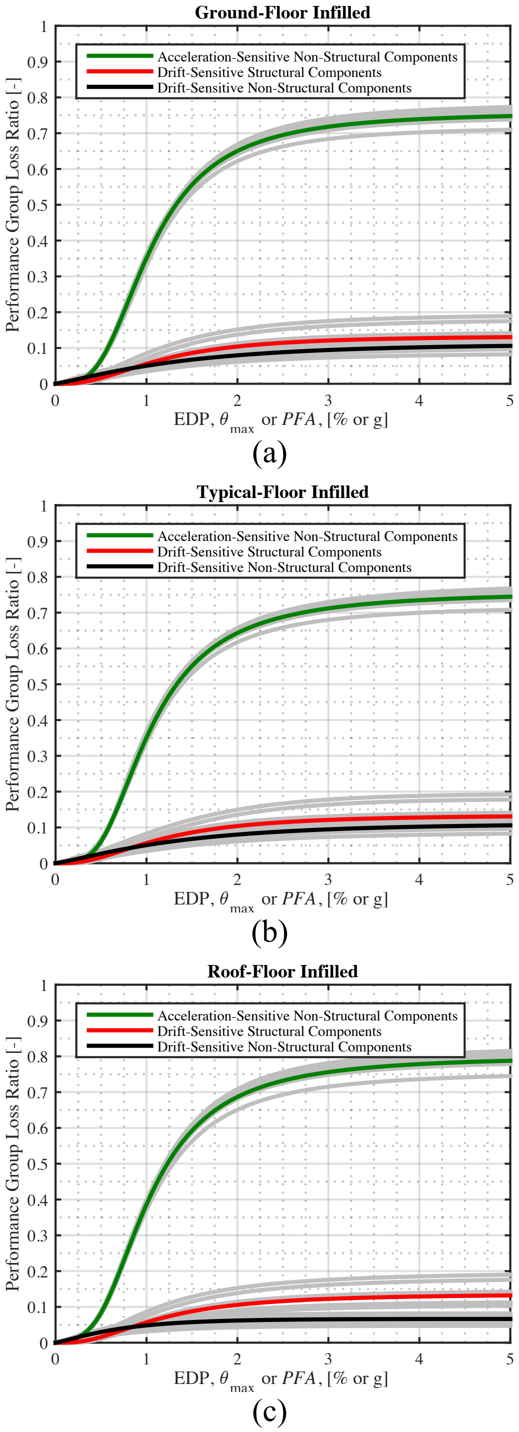


Figure 2: Flowchart illustrating the necessary steps for the calibration and derivation of normalised SLFs

This toolbox was developed for the automated creation of SLFs through regression analysis on the results of Monte Carlo simulation of component damage states and subsequent repair costs, also accounting for damage correlation among different components. It allows quick generation of SLFs following the definition of a damageable component inventory, damage states, fragility functions, repair actions and repair costs. The toolbox allows for a good degree of tailored use depending on user needs to be used to derive and fit the SLFs following Monte Carlo simulation. Finally, a generalized set of SLFs which are normalised directly to the total expected repair cost was obtained. This implies that should a representative normalizing value be known such as the total replacement cost, for the building typology (or taxonomy class), estimates of repair costs could be quickly obtained and integrated into engineering practice. As such, a clearer disaggregation of the repair costs associated with each PG can be observed and the estimation becomes independent of the total replacement value of the structure. In the end, generalised SLFs expressed in terms of a normalised loss ratio corresponding to the contribution of each PG were derived and illustrated in Figure 3. For more details regarding the development and calibration of generalized SLFs, see Nafeh and O'Reilly (2023)



(a)

(b)

(c)

Figure 3: Derived set of generic storey-loss functions relating the loss ratio of a given performance group

to the corresponding EDP and considering distinct storey typologies

3. CASE STUDY ASSESSMENT OF LOSS ASSESSMENT METHODOLOGIES

A performance assessment of the aforementioned simplified methodologies was carried out. The SLF-based method and *Sismabonus* were compared to the more rigorous component-based approach outlined in FEMA P-58. Seventy non-ductile infilled RC case study structures were considered for the comparison, which are accessible here: [https://github.com/gerardjoreilly/Infilled-RC-Building-Database.](https://github.com/gerardjoreilly/Infilled-RC-Building-Database)

NLTHA using MSA (Jalayer and Cornell 2009) was performed using hazard-consistent ground motion records to characterize the seismic response of the case study building population. The average spectral acceleration (Sa_{avg}) was adopted as the IM. Hazard was characterized using the OpenQuake engine (Pagani et al. 2014) along with the 2013 Euro-Mediterranean seismic hazard model (ESHM13) (Woessner et al. 2015). The mean hazard curves are illustrated in Figure 4.

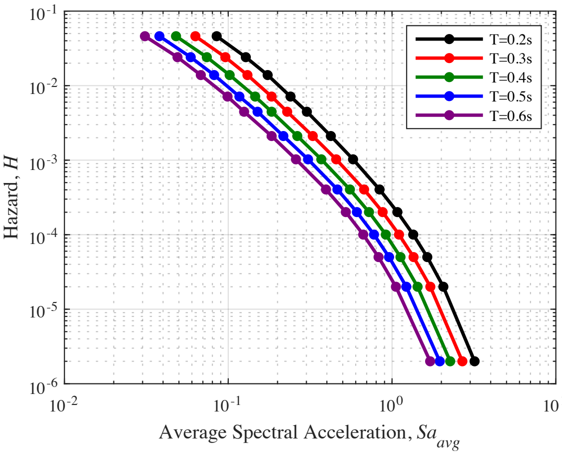


Figure 4: Mean hazard functions expressed in terms of the annual frequency of exceedance versus the intensity measure level considering the fundamental periods of the case study buildings

Ground motion records were selected from the NGA-W2 database using the conditional mean spectrum (Kohrangi et al. 2017) for Sa_{avg} and the geometric mean of the two components was considered for the selection. MSA was conducted for nine intensity measure levels corresponding to return periods of 22, 42, 72, 140, 224, 475, 975, 2475 and 4975 years to characterize the structural response from initial damage of the masonry infill panels right up to global structural collapse. An excerpt of a subset of selected ground motions is presented in Figure 5. Structural performance in terms of PSDs and PFAs was characterized at each intensity measure level and served as input for the vulnerability component in the PACT tool.

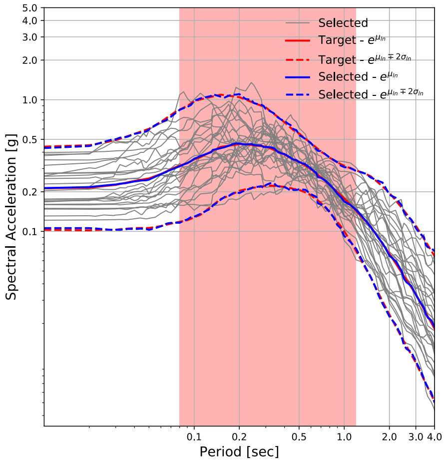
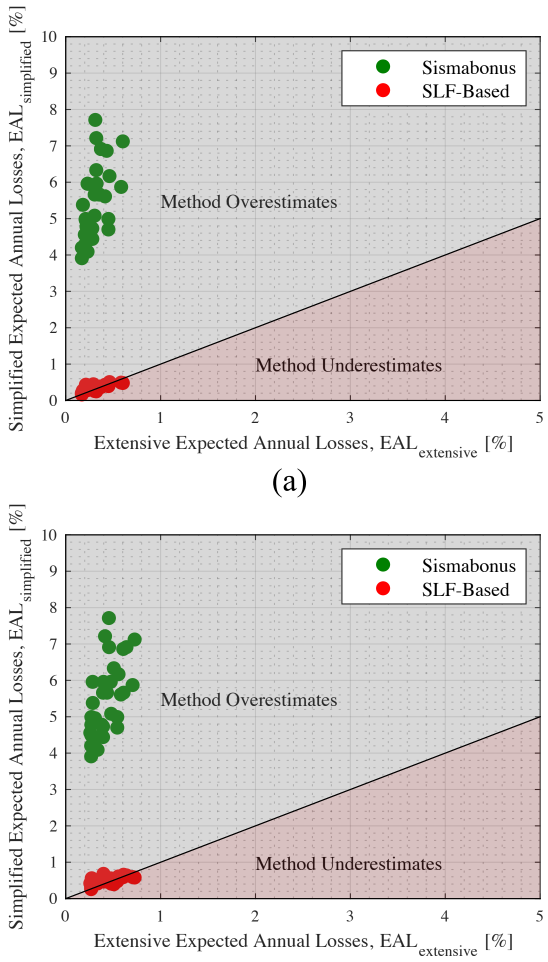


Figure 5: Ground motion selection using the conditional mean spectrum (target) corresponding to a single case (return period of 475 years for Sa_{avg} (T=0.4s))

For the application of *Sismabonus* concerning the estimation of the EAL values, the procedure outlined in Cosenza *et al.* (2018) and described qualitatively in the previous section was used. For the application of the SLF-based approach, the results of NLTHA were used for the identification of the expected loss ratios considering the structural response at multiple intensity measure levels. For the calculation of the MAFE, λ was calculated by convolving the hazard function at the chosen site with the intensity measure levels considered for the selected site. Figure 6 illustrates the EAL values evaluated following the two simplified approaches. These values were also compared to the values obtained following extensive assessment. Figure 6 highlights an overestimation in the values of the EAL when the simplified approach in *Sismabonus* was employed. The main differences between the estimates obtained using the *Sismabonus* approach and PACT invariably arise from the simplifications required to integrate the procedure outlined in *Sismabonus* with existing codes of practice and make it more accessible to practising engineers. One of the main simplifications is the expected loss ratios for each LS being fixed percentages of the replacement cost, regardless of building typology or occupancy. This aspect was further investigated in O'Reilly *et al.* (2018) by comparing the expected loss ratio at each LS from detailed analysis with the fixed expected loss ratios outlined in the guidelines. It was shown that the expected loss ratios at each LS computed using detailed analysis were much lower than the fixed values specified in the guidelines, explaining the difference in magnitude between the EAL values observed in Figure 6.

Moreover, it is evident through the illustrative comparison presented in Figure 6 that the SLF-based approach yielded relatively good estimates when compared to the extensive methodology. This is due to the adaptability of the proposed storey loss functions in characterising economic losses closely related to the structural response expressed in terms of the seismic demand (i.e. PSD and PFA). Based on these promising results regarding the accuracy of SLF-based loss assessment, the integration of such simplified tools for the response estimation of structures in terms of demand parameters (i.e. PSDs and PFAs) is appealing to analysts. This integration could encourage a more demand-based estimation of the associated losses at limit-states or at different levels of ground-shaking intensity. This is contrary to pre-calibrated and fixed LS loss ratios which are currently adopted in *Sismabonus*, whose accuracy and outputs may not reflect that of a more detailed component-based analysis.



(a)

(b)

Figure 6: Comparison of SLF-based approach and the simplified methodology in Sismabonus in terms of the evaluation of the expected annual loss for (a) GLD and (b) SSD case study structures.

4. CONCLUSIONS

Recent years have witnessed the evolution in seismic risk assessment from traditional objectives related mainly to building performance to other issues like economic loss and life safety. Furthermore, the trade-off between simplicity and accuracy remains an open challenge for researchers in an attempt to provide practitioners and decision-makers with simplified tools to accurately characterise the seismic performance of structures. Additionally, the evaluation of the direct monetary losses sustained in seismic events, through metrics such as the expected annual losses (EAL) for example is paramount for existing reinforced concrete (RC) structures with masonry infills due to their prevalence. In loss-based analyses, component-based approach is heavily dependent on the results of NLTHA which renders it equally heavy with regards to the computational burden. This has been further demonstrated through the introduction of seismic risk guidelines in Italy. Such guidelines offer a simple and practice-oriented approach that is geared towards widespread application. However, further scrutiny has shown that with respect to more exhaustive loss assessment methods, these simplified approaches such as *Sismabonus* may possess some limitations and drawbacks that can be improved in future revisions. This was seen here for the case of non-ductile infilled RC buildings, which was seen to give loss estimates that significantly differed to those obtained from the more rigorous analysis described in FEMA P-58. A solution in the form of generalised storey loss functions was discussed concerning how their integration in future revisions of these guidelines may be beneficial. The performance of the proposed SLF-based methodology in accurately evaluating the direct economic losses due to ground-shaking was validated within a comparative case study application. The results highlighted the reliability and consistency of the proposed approach when compared to the results of extensive analysis performed in PACT on numerical models with hazard-consistent ground motions. Some of the work and tools developed in recent years that would facilitate such a usage were described. Again, within the scope of providing a practitioner-friendly tool that could help build a more robust future revision, some of the recent work done in this regard was described.

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