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Simplified tools for the risk assessment and classification of existing buildings

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Abstract

In recent decades, the seismic assessment of existing buildings has developed significantly from traditional objectives focusing on ensuring life-safety of buildings to more advanced metrics considering potential economic losses. Italy has made notable developments in this regard with the introduction of the so-called *Sismabonus* seismic risk assessment and classification guidelines. These guidelines consider more advanced metrics of seismic performance and use vast amounts of existing data following past earthquakes and specialized studies. They offer a simple and practitioner-oriented approach that is geared towards widespread application. Further analysis has shown that when scrutinized with respect to more exhaustive risk assessment methods, the simplified approaches adopted within *Sismabonus* may possess some limitations and drawbacks. Recent research, however, has shown that with some modest adjustments and modifications, these simplified methods can be notably improved without any notable penalties in applicability in a practitioner setting. This paper discusses some of these recent developments in tools and approaches and describes how they may be integrated in future revisions of risk assessment guidelines.

Keywords: seismic risk, assessment, loss estimation, performance.

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1. Introduction

Notable developments have been made in recent decades for the seismic assessment of existing buildings, with objectives focusing on the life-safety of buildings evolving into more modern objectives incorporating economic

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losses (Calvi et al. 2014). Despite the limited number of lives lost, the economic impact and overall disruption caused by the 1994 Northridge earthquake in the US suggested that a more advanced approach was needed into how performance of structures ought to be defined. Similar observation were also reported after the 2009 earthquake in L’Aquila (Salvatore et al. 2009) and the 2016 earthquakes in Central Italy (De Luca et al. 2018).

The Italian Ministry of Infrastructure and Transport issued Decreto Ministeriale 58/2017 (Decreto Ministeriale 2017) in 2017 describing a framework for the classification of seismic risk in buildings, more commonly referred to as *Sismabonus*. This *Sismabonus* framework is described in detail in Cosenza *et al.* (2018) using the data on repair costs collected following the L’Aquila earthquake (Dolce and Manfredi 2015) as its basis and approach is integrated with the Italian building code (NTC 2018). In essence, it provides practitioners with a simple framework to assess the overall seismic performance of buildings and qualitatively shows how they may be improved via retrofitting.

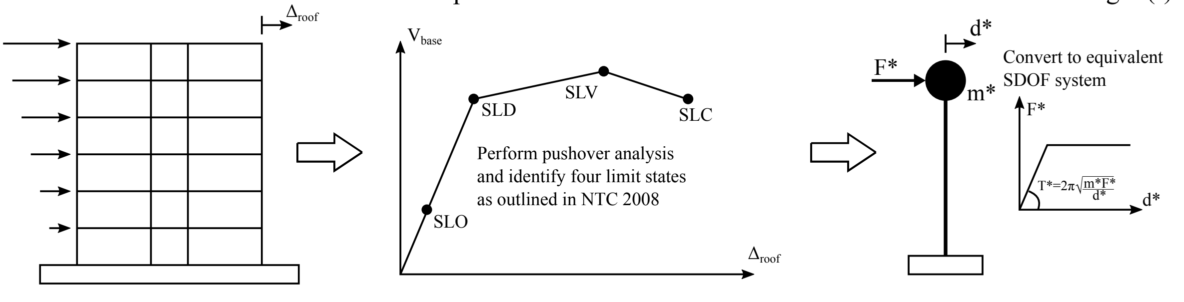
Despite the several advantages and benefits to be gained from such an accessible and straightforward framework (e.g., the Italian governmental scheme launched in 2020 (Decreto Ministeriale 2020)), research has shown that it may possess some limitations with respect to more rigorous risk analyses. However, with some modest adjustments and modifications, the assessment approach utilized in *Sismabonus* could be improved without any penalty in applicability in a practitioner setting. This paper first outlines the general steps involved in *Sismabonus* and then discusses some of these recent research developments in tools and approaches which may be integrated in future revisions these guidelines.

Nomenclature

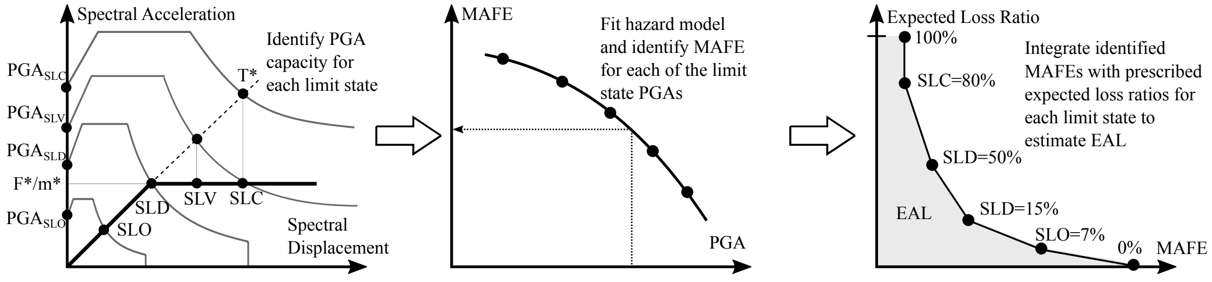
CSM	Capacity spectrum method
DCM	Displacement coefficient method
EAL	Expected annual loss
FEMA	Federal emergency management agency
IS-V	Life safety index
LS	Limit state
MAFE	Mean annual frequency of exceedance
MSA	Multiple stripe analysis
PBEE	Performance-based earthquake engineering
PGA	Peak ground acceleration
PEER	Pacific earthquake engineering research
RC	Reinforced concrete
SDOF	Single degree of freedom
SLO	Operational limit state
SLD	Damage control limit state
SLV	Life safety limit state
SLC	Collapse prevention limit state
SLF	Storey loss function
Δ_{roof}	Roof displacement
V_{base}	Base shear
F^*	Equivalent SDOF force
d^*	Equivalent SDOF displacement
m^*	Equivalent SDOF mass
T^*	Equivalent SDOF period
T	Period
q	Behaviour factor
ζ	Strength reduction factor
μ	Ductility
λ_{LS}	MAFE

2. Overview of seismic risk classification guidelines

The *Sismabonus* guidelines aim to incorporate some of the more recent advancements in the field of seismic risk assessment into a procedure that is both straightforward to implement, and integrates well with the existing building in Italy. The guidelines focus on two specific aspects regarding buildings: life-safety and expected annual loss (EAL), and provide a classification system with which practitioners can assess the current status of buildings and demonstrate improvements via different retrofitting measures. The procedure is illustrated schematically in Fig. 1 and shows how only a pushover analysis is required to identify the four limit states described in Italian national code (NTC 2018). These correspond to: operational (SLO), damage control (SLD), life safety (SLV) and collapse prevention (SLC). By identifying these four limit states for a building and converting it to an equivalent single degree-of-freedom (SDOF) system, as shown in Fig. 1(b) and (c), the intensity required to exceed each limit state is identified in Fig. 1(d). This intensity is defined in terms of the peak ground acceleration (PGA) of the code response spectrum and from this, the mean annual frequency of exceedance (MAFE) is determined from a site hazard model, as shown in Fig. 1(e). Once the MAFE for each limit state is established, these are integrated with prescribed values of expected loss ratio for each limit state outlined in D.M. 58/2017 to compute the EAL as the area under the loss curve illustrated in Fig. 1(f).



(a) Static Pushover Analysis (b) Identification of Limit States (c) Conversion to Equivalent System



(d) Identify PGA of LSs (e) Identify MAFE of LSs (f) Compute EAL

Fig. 1. Illustration of various steps within the Italian seismic risk classification scheme described in D.M. 58/2017 (Adapted from O'Reilly *et al.* (2018))

This is quite a simple approach as it requires the analyst to conduct just a pushover analysis and eliminates the need for many of the steps involved in the Pacific Earthquake Engineering Research Center's performance-based earthquake engineering (PEER-PBEE) loss estimation methodology described in FEMA P-58 (FEMA 2012), for example. The end result of the guidelines is that an EAL is computed and classified within a letter-based system similar to that initially proposed by Calvi *et al.* (2014). In addition to the EAL-based score that classifies the seismic performance in terms of economic loss, another score is attributed based on the collapse safety of the building. This is determined based on the ratio of the PGA required to exceed the life-safety limit state (PGA_{SLV} in Fig. 1(d)) to the PGA demand that a new structure would be designed for at the same limit state. Using the demand to capacity ratio computed as function of the PGA at the SLV limit state, termed IS-V, another letter-based score is attributed to the building and the overall ranking is determined as the more critical of the EAL-based and IS-V-based ranks, which are shown in Table 1.

Table 1. Seismic performance classification ranking system as a function of both EAL and IS-V

EAL Classification Range	Life Safety Index Classification Range	Classification Ranking
EAL ≤ 0.5%	100% < IS-V	A+
0.5% < EAL ≤ 1.0%	80% ≤ IS-V < 100%	A
1.0% < EAL ≤ 1.5%	60% ≤ IS-V < 80%	B
1.5% < EAL ≤ 2.5%	45% ≤ IS-V < 60%	C
2.5% < EAL ≤ 3.5%	30% ≤ IS-V < 45%	D
3.5% < EAL ≤ 4.5%	15% ≤ IS-V < 30%	E
4.5% < EAL ≤ 7.5%	IS-V ≤ 15%	F
7.5% < EAL		G

3. Possible limitations

3.1 Expected annual loss

Using this simplified procedure outlined in *Sismabonus*, O'Reilly *et al.* (2018) assessed the performance of a case study school building at two site locations in Italy to establish its seismic performance and compare it with the rigorous approach outlined in FEMA P-58. A detailed numerical model of the structure was analyzed using static pushover analyses, its limit states identified and its equivalent SDOF systems determined using the N2 method (Fajfar 2000), shown in Fig. 1(a) to (c). The MAFE for each limit state was determined and the EAL computed, with the final values are reported in Table 2. In addition, the life safety index (IS-V) was also computed as the ratio of the PGA_{SLV} determined in Fig. 1(d) and the PGA corresponding to a design return period of 712 years for school buildings. The scoring for both of these criteria was determined, and the resulting overall seismic classifications of the building are listed in Table 2. Also shown are the EAL values computed following the FEMA P-58 approach described in detail in O'Reilly *et al.* (2018).

By comparing the values presented in Table 2 first, it is clear that the life safety index is the governing criteria and determines the overall seismic classification in both cases. Comparing the EAL values reported in Table 2 with those computed using the rigorous approach in FEMA P-58, some discrepancy can be seen in the results plotted in Figure 2. The overall magnitude of the EAL values computed using the simplified method is much higher than those computed following the rigorous approach. While the overall magnitude differs, the overall trend and relative differences between the different typologies and site locations remain the same. This suggests that the general method is still a decent indicator of relative performance, but the absolute value may need further refinement

Table 2. EAL and IS-V values of a case study school building in Italy

Site Location	High	Medium
EAL	0.84%	0.60%
EAL Classification	A	A
IS-V	0.60	0.79
IS-V Classification	C	B
Overall Classification	**C**	**B**
EAL (FEMA P-58)	0.35%	0.28%

These differences 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 limit state being fixed percentages of the replacement cost, regardless of building typology or occupancy. This aspect was further investigated O'Reilly *et al.* (2018) by comparing the expected loss ratio at each limit state from detailed analysis with the fixed expected loss ratios outlined in the guidelines. It was shown that the expected loss ratios at each limit state 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 2. This was especially the case at the SLO and SLD limit states which are weighted much more heavily during the EAL integration. Another issue that is not currently considered is regarding the building occupancy type (i.e., apartment, school or office building), where no distinction is made in the Sismabonus guidelines between the different types of building occupancy for the building loss ratio at each limit state. Taghavi and Miranda (2003) highlighted the importance of building occupancy type on the distribution of economic loss between the different elements of a building, hence it ought to be considered further.

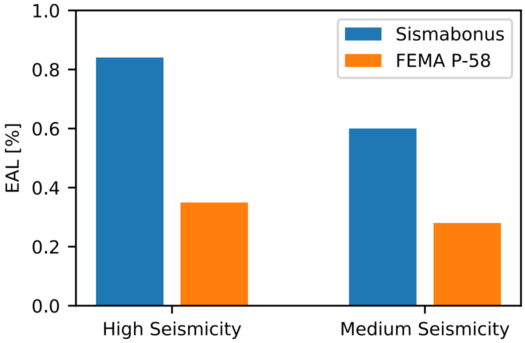


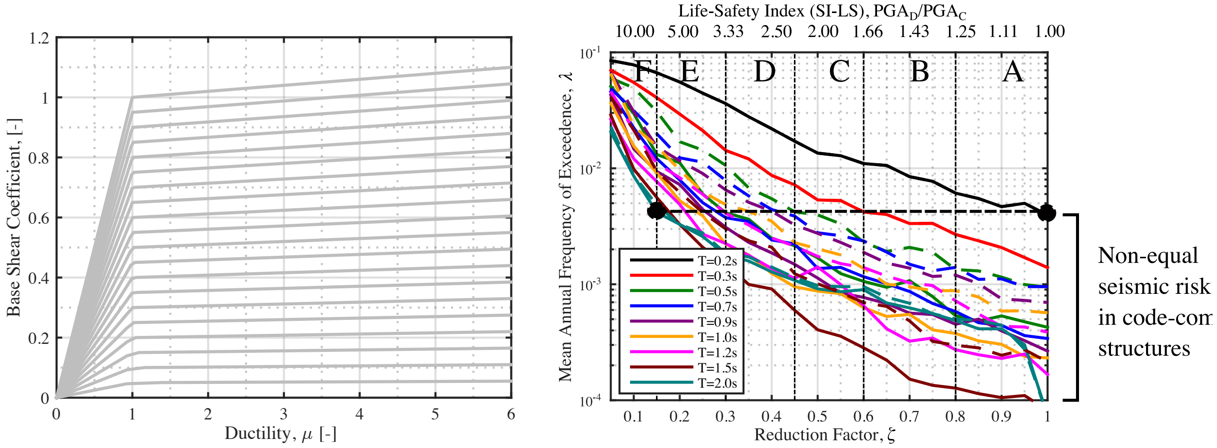
Figure 2. Comparison of the EAL ratios from detailed analysis using FEMA P-58 and those estimated from simplified analysis in Sismabonus

3.2 Collapse safety

In addition to the inaccuracies in estimating economic losses, another limitation of the current risk classification scheme is the lack of uniformity of risk estimates used to determine the collapse safety of structures. This was outlined in studies such as Iervolino *et al.* (2018) and Shahnazaryan and O'Reilly (2021), for example. The issue lies in the use of load-based quantities to infer risk estimates, which is illustrated below.

A simple study is presented here to demonstrate such implications using code-compliant and non-compliant SDOF systems. Several SDOF oscillators were modelled with a bilinear hysteretic response and fundamental period, T, ranging from 0.2 to 2 seconds and designed for two ductility classes: medium and high, corresponding to behaviour factors, q, for reinforced concrete (RC) frames of 3.90 and 5.85, respectively. The systems were designed for a soil class C site in L'Aquila, Italy, whose peak ground acceleration (PGA) was identified as 0.26g. Most importantly, a strength modification factor, ζ, was applied to weaken the overall strength capacity of the SDOF systems and act as a proxy for non-code compliant or existing structures. It ranged between 0.05 (i.e., weakest) and 1.0 (i.e., code-compliant) with an increment of 0.05. The effect of ζ on the lateral response of the SDOF oscillators is illustrated in Figure 3(a), expressed in terms of the base shear coefficient (i.e., design force normalised by total seismic weight) and ductility. A series of multiple stripe analysis (MSA) (Jalayer and Cornell 2009) was performed using hazard-consistent ground motion records selected following a probabilistic seismic hazard assessment using the OpenQuake engine to characterise the seismic response of the SDOF oscillators.

The results, expressed in terms of the MAFE of a limit state, λ_{LS}, defined at a ductility of $\mu_{LS} = 4$ are shown in Figure 3(b). The seismic risk class of each SDOF oscillator was determined according to the *Sismabonus* classification system based on the life-safety index, defined as the ratio between the PGA demand at a return period of 475 years and the equivalent PGA capacity of the SDOF systems (i.e., PGA_D/PGA_C). Figure 3(b) illustrates the variability in the actual risk characterised via λ_{LS} versus T and ductility class. Additionally, the trends between λ_{LS} and ζ are demonstrated. Overall, it is evident that the seismic design and response estimation implemented in this manner does not result in uniform risk solutions. The shortcomings of this become more evident when assessing existing structures, where the capacity is generally not code-compliant (i.e., $\zeta < 1$). Figure 3(b) shows that many different risk classes can result for the same λ_{LS} depending on its period and ductility class. For example, following the horizontal line sketched in Figure 3(b), a T=2.0s system with medium ductility class is classified F, whereas a T=0.2s system also with the same ductility class is classified A, despite the same level of actual risk. Furthermore, a vertical comparison in Figure 3(b) highlights that code-compliant systems possess widely varying values of λ_{LS}.



(a) (b)

Figure 3: (a) Example of SDOF oscillators (T=0.3s and q=3.90) illustrating the degradation in lateral strength with respect to the code-compliant value for the design base shear; (b) non-uniformity of risk for SDOFs for both medium (solid lines) and high (dashed lines) ductility classes versus periods of oscillation, T, and strength modification factor, ζ

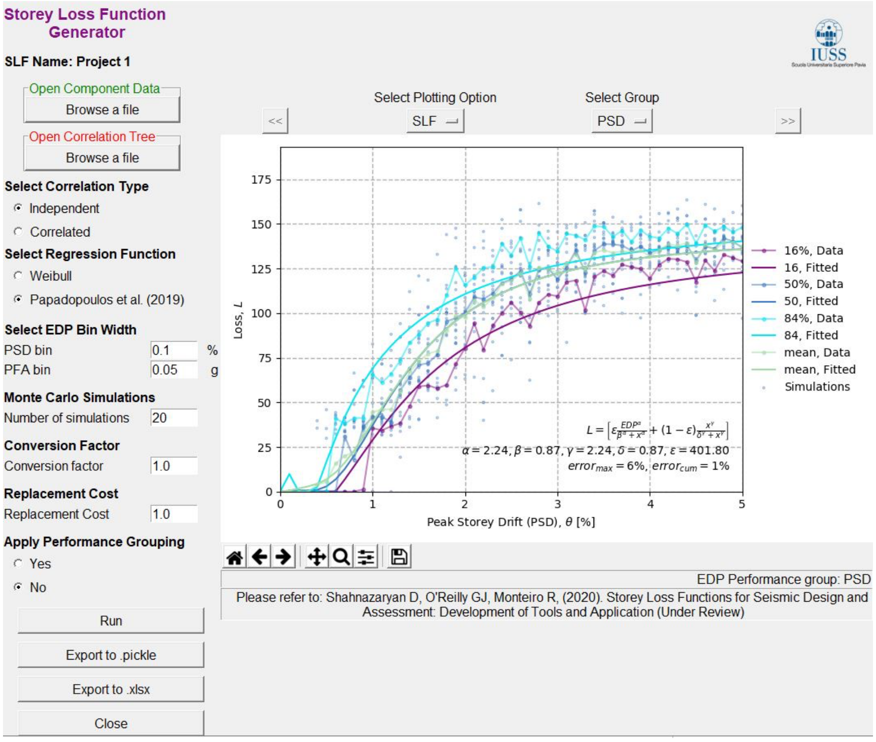
Overall, Figure 3(b) gives and clear and straightforward illustration of the non-uniformity of current code-based design and assessment guidelines. This observation infers that more effort should be made to express seismic risk via methodologies that better represent demand and capacity while still offering a reduction in computational cost without compromising accuracy.

4. Possible improvements

4.1 Expected annual loss

Section 3.1 discussed how the estimation of seismic losses was typically conservative and lacking a degree of detail that is perhaps required. That said, performing detailed analysis requires several non-linear dynamic analyses and estimates of individual repair costs and inventory quantities that is currently beyond the scope of most practical settings. Instead of conducting building-specific loss estimation (FEMA 2012), a simplified alternative using storey loss functions (SLFs) may be used. The use of SLFs entails the reduction of computational effort by providing ready-made loss functions that describe the repair costs over a predefined building inventory of damageable elements in a simplified manner. As a results, the amount of data required to be handled for the building’s inventory when estimating losses is significantly reduced when such SLFs are made available. These SLFs have been recently implemented, for instance in Ramirez and Miranda (2009) n the US, in Silva et al. (Silva et al. 2020) for steel buildings in a European context. To fill the missing gap for the development of these functions ad-hoc, Shahnazaryan et al. (2021) have developed a toolbox for automated production of SLFs through regression analysis using the results of random sampling of component damage states and costs, including damage correlation among components, and whose interface is illustrated in Figure 4. It allows quick generation of SLFs and can be easily tailored and personalised for users depending on damageable inventories, repair actions and repair costs to arrive at more fine-tuned SLFs. The toolbox requires knowledge of component quantities, fragility, and consequence functions as inputs to generate FEMA P-58 compatible SLFs.

Through its application to an RC school building in Italy and subsequent loss assessment in a comparative setting in Shahnazaryan et al. (2021), whose results are repeated here in Figure 5, it was shown to have similar outputs with respect to the more rigorous component-based loss assessment described in FEMA P-58. Good match in EAL as well as in distribution of losses among different performance groups was observed further highlighting the quality of the developed SLFs via the toolbox and its applicability for accurate but simple loss assessment.



Storey Loss Function Generator

SLF Name: Project 1

Open Component Data
Browse a file

Open Correlation Tree
Browse a file

Select Correlation Type
● Independent
○ Correlated

Select Regression Function
○ Weibull
● Papadopoulos et al. (2019)

Select EDP Bin Width
PSD bin 0.1 %
PFA bin 0.05 g

Monte Carlo Simulations
Number of simulations 20

Conversion Factor
Conversion factor 1.0

Replacement Cost
Replacement Cost 1.0

Apply Performance Grouping
○ Yes
● No

Select Plotting Option: SLF
Select Group: PSD

$L = \left[\varepsilon \frac{EDP^{\alpha}}{\beta^{\alpha}+x^{\alpha}} + (1-\varepsilon)\frac{x^{\gamma}}{\delta^{\gamma}+x^{\gamma}}\right]$

$\alpha = 2.24, \beta = 0.87, \gamma = 2.24, \delta = 0.87, \varepsilon = 401.80$

$error_{max} = 6\%, error_{cum} = 1\%$

EDP Performance group: PSD

Please refer to: Shahnazaryan D, O'Reilly GJ, Monteiro R, (2020). Storey Loss Functions for Seismic Design and Assessment: Development of Tools and Application (Under Review)

Figure 4. Illustration of the storey loss function generator interface available at https://github.com/davitshahnazaryan3/SLFGenerator

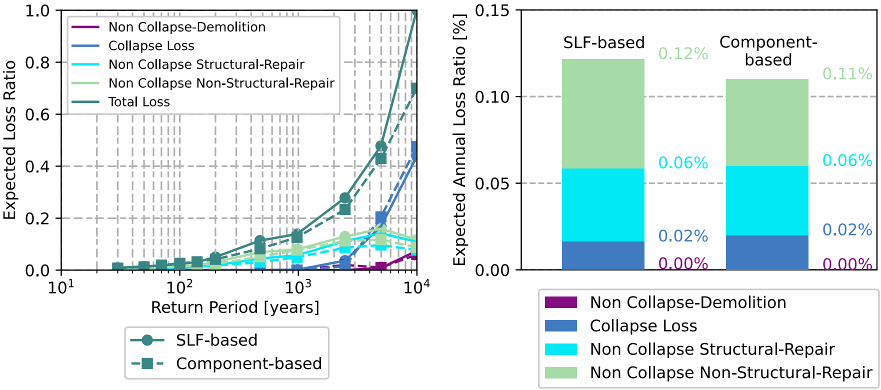


Figure 5. (left) Vulnerability curves and (right) expected annual loss ratio showing the breakdown between different contributors in a comparative assessment between an SLF-based and component-based approach (Shahnazaryan, O’Reilly, and Monteiro 2021)

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. storey drifts and peak floor accelerations) 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 limit state loss ratios which are currently adopted in *Sismabonus*, whose accuracy and outputs may not reflect that of a more detailed component-based analysis (Figure 2). Future developments may therefore consider the integration of this simplified tool with typology-based generalized SLFs. Doing so, would offer an additional decent trade-off between accuracy and simplicity and an easy of applicability for practitioners. This has been recently explored for non-ductile infilled frames (Nafeh and O’Reilly 2022), where the notion of a normalized SLF for specific typologies can be seen in Figure 6. This implies that should a representative normalizing value be known for the building typology (or taxonomy class), estimates of repair costs could be quickly obtained and integrated into engineering practice.

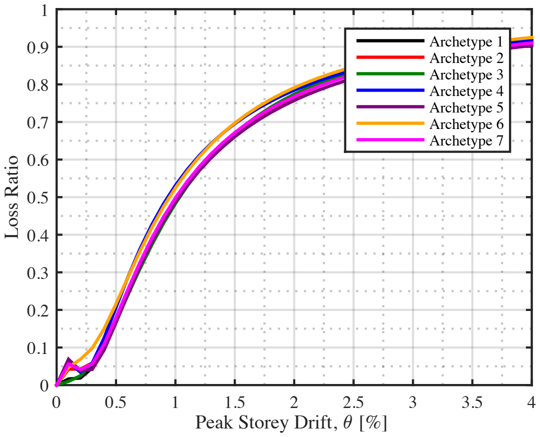


Figure 6. Comparison of the normalised storey loss functions for several infilled frame archetypes showing a relatively consistent trend among different buildings (Nafeh and O'Reilly 2022)

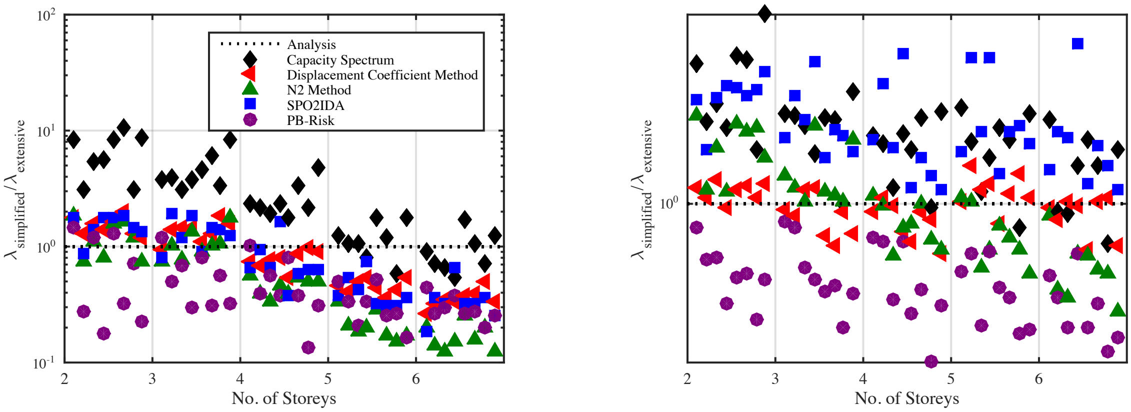
4.2 Collapse safety

Section 3.2 highlighted the limitations of *Sismabonus* to characterize the life-safety of existing structures when compared to risk-based quantities like MAFE. A possible improvement for the quantification of seismic intensities and subsequently the characterisation of collapse safety is the application of the simple pushover-based methodology *PB-Risk* developed by Nafeh and O'Reilly (2022a) for infilled RC frames.. The method estimates the seismic response using the results obtained from pushover analysis along with the first-mode parameters from eigenvalue analysis as inputs. Subsequently, the seismic intensity required to attain a particular limit-state of interest expressed in terms of average spectral acceleration, Sa_{avg}, can be identified. The method is relatively fast and straightforward, which is then integrated with closed-form expressions for the probabilistic characterization of the associated risk in single structures at any location of interest. Additionally, robustness, accuracy and consistency were highlighted in Nafeh and O'Reilly (2022a) despite the inherent simplicity of the method and the improvement offered compared to non-linear time-history analyses. It is quick and easy to implement within a practical and code-based setting and could be easily adopted within risk classification guidelines.

The application of the *PB-Risk* methodology was demonstrated via several case study applications in Nafeh and O'Reilly (2022a), and its robustness in characterising seismic risk with respect to other simplified non-linear static formulations for infilled frame buildings is also shown here. The *PB-Risk* method was scrutinized with respect to other non-linear static procedure methods such as capacity spectrum method (CSM) (Freeman 1998), N2 method (Fajfar 2000), which is used in *Sismabonus*, displacement coefficient method (DCM) and SPO2IDA (Vamvatsikos and Cornell 2005) for infilled RC frames structures. The results of their application, shown in Figure 7, either consistently underestimated or overestimated the risk of exceeding a given limit state when compared to the results obtained from detailed non-linear time-history analyses. This highlights the inconsistency and general difficulty of existing methods when applied to infilled RC frame buildings but also the suitability of *PB-Risk*.

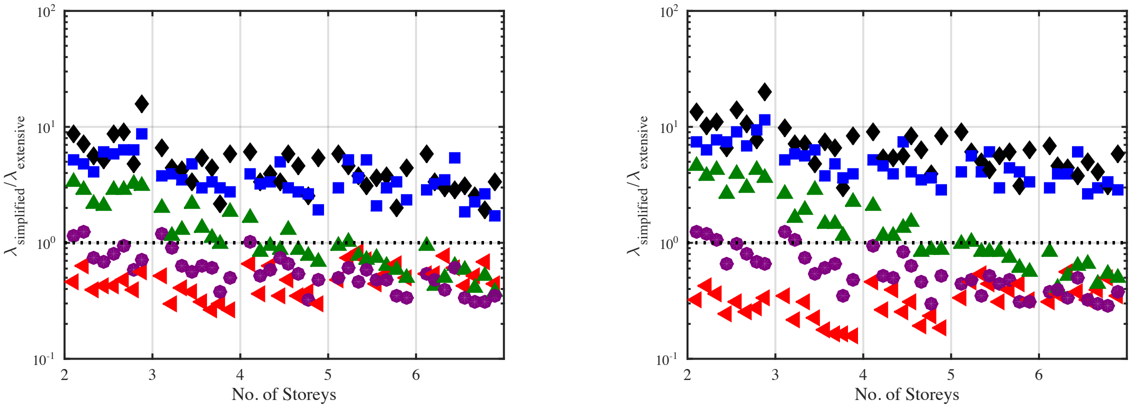
5. Summary

Recent years have seen the evolution of seismic risk assessment from traditional objectives focusing solely on building performance to other issues like economic loss and life safety. This has been further demonstrated through the advent of seismic risk assessment and guidelines in Italy. They offer a simple and practice-oriented approach that is geared towards widespread application. However, further scrutiny has shown that with respect to more exhaustive risk assessment methods, these simplified approaches to compute economic losses or assess collapse safety adopted within *Sismabonus* may possess some limitations and drawbacks that ought to be improved in future revisions of the guidelines.



(a) Operational (SLO)

(b) Damage control (SLD)



(c) Life safety (SLV)

(d) Collapse prevention (SLC)

Figure 7: Mean annual rate of exceeding the demand-based thresholds associated with each of the NTC2018 limit-states

This was seen here for the case of a school building, which when assessed via the current simplified approach was seen to give loss estimates that significantly differed to those obtained from more rigorous analysis. Some potential solutions in the form of storey loss functions were discussed in relation to how their integration in future revisions of these guidelines may be beneficial. Some of the work and tools developed in recent years that would facilitate such a usage were described.

Regarding collapse safety, a brief example was shown to again show how current codes do not provide uniform levels of risk in new designs and that also, the methods used to assess existing ones possess some significant limitations. 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. It was also shown via a simple example how this would compare in terms of risk estimation when evaluated against more rigorous analysis and other contemporary methods.

Overall, this paper has discussed some of these recent developments in tools and approaches and describes how they may be integrated in future guidelines.

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