SEISMIC RISK CLASSIFICATION OF NON-STRUCTURAL ELEMENTS

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Abstract

Non-structural elements (NSEs) are those not forming part of a building's structural load-bearing system but are nevertheless subjected to dynamic forces and deformations during ground shaking. In terms of their role in building cost, NSEs make up approximately 82%, 87% and 92% of the total monetary investment for office, hotel and hospital buildings, respectively. Additionally, it has been shown that for a typical school building in Italy, NSEs comprise the majority (>60%) of the direct monetary losses induced at frequent levels of ground shaking. These two points alone highlight the critical nature of NSEs both from an initial investment and potential monetary loss perspective. The ability to quantify the seismic risk associated with structural and non-structural elements is a critical aspect of earthquake engineering. While methods to improve the understanding of structural response to earthquake shaking and how to quantify their risk have been studied, NSEs have recently emerged as a crucial aspect to address given their pertinence in overall building performance. This paper describes the formulation of a risk quantification methodology for NSEs whereby the mean annual frequency of exceeding an NSE's damage state is computed and rated as part of a risk classification scheme. The basis of the methodology is described followed by example implementations, where the details surrounding hazard, structural and non-structural response are quantified consistently, ensuring that uncertainties are also incorporated to be in line with modern performance-based earthquake engineering. This relates to both storey drift-sensitive and floor acceleration-sensitive non-structural elements that typically comprise most building fixtures and fittings in addition to the contents themselves. The result is a simple but effective methodology that may be used to directly quantify and rank the risk associated with NSEs from a life safety, functionality and economic loss perspective. It may be implemented as part of a prioritisation scheme for building retrofit or also serve as a commercial instrument for NSE manufacturers, whereby their products can be marketed as a having a certain rating class, to demonstrate superior seismic resilience with respect to others.

Keywords: seismic performance; risk classification; non-structural elements; design; assessment

1. Introduction

Components that do not form part of a building's structural load-bearing system, but are in any case subjected to shaking and deformations during earthquakes are referred to as non-structural elements (NSEs). Past earthquakes in different regions around the world have highlighted damage to NSEs [1,2]. This may be due to many design codes' approach to ensuring the satisfactory seismic performance of buildings at ultimate limit states and avoid loss of life through global collapse. European [3], American [4] and New Zealand [5] guidelines, for example, focus on the structural behaviour during strong ground shaking via their *no-collapse*, *collapse prevention* and *ultimate limit state* prescriptions, respectively. Some drift and floor acceleration checks are then carried out to avoid excessive NSE damage during more frequent events. For the NSEs themselves, simplified force-based procedures are also prescribed to determine the required lateral force resistance of the NSE and supports within the structure, although a recently proposed displacement-based methodology [6] advocates a more consistent approach.

For what concerns building costs, NSEs have been shown [7] to make up approximately 82%, 87% and 92% of the total monetary investment for office, hotel and hospital buildings, respectively, whereas for a typical school building in Italy, they have been shown [8] (Fig. 1) to represent the majority (>60%) of the direct monetary losses induced at lower return periods. In addition to losses, life safety risks due to falling objects or increased downtime due to leaking pipes, for example, are likely outcomes. Given that the ultimate behaviour of a structure is usually focused on in design codes and the approximate nature of the design for NSE restraints, it is not easy to obtain the actual margin of safety for a building's NSEs. Demands on the NSEs may be computed as part of design code provisions, but are a function of the main structure's actual response. Considering the conservative nature of these codes for structural design, accurate quantification of NSE performance cannot reasonably be easily obtained without some form of detailed dynamic analyses on the main structure and its NSEs. In Italy, the seismic risk of buildings may be classified by different ratings using the *Sismabonus* guidelines [9]. It uses the more critical of a collapse safety index (IS-V) and expected annual losses (EAL) ratio, as shown in Fig. 2. With such guidelines, the quantification and classification of seismic risk for existing buildings can be carried out in a clearer and more straightforward manner, fostering an improved way demonstrate how to improve the seismic resilience of buildings.

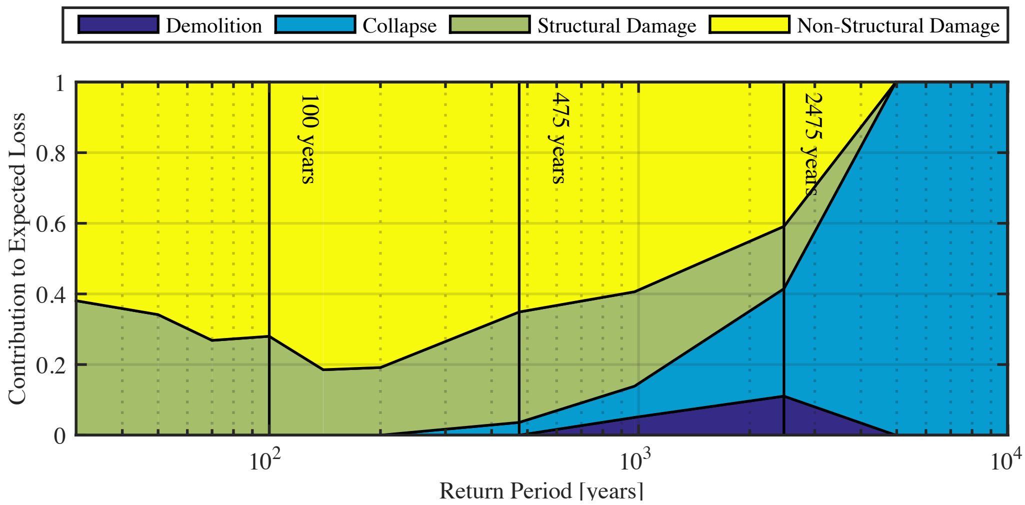

Fig. 1 – Relative contribution to losses with increasing return periods of ground shaking [8]

This paper examines a recently developed seismic risk classification scheme for NSEs [10] and how it may be implemented to quantify the level and types of risk posed by various NSEs on the built environment. It utilises simplified relationships to quantify the risk of increasing levels of NSE damage states in a probabilistic manner. The relevant sources of uncertainty typical of seismic response and damage assessment are incorporated in the process. This gives a methodology that is simple in its implementation, since relatively little dynamic analysis is required, and robust in its characterisation of NSE performance to be fully in line with the goals of modern performance-based earthquake engineering [11]. Such results may then be used within a tentative classification scheme similar to *Sismabonus* to rank and classify the performance of NSEs. The discussion here is limited to a *single structure-single NSE* context, but may be extended to evaluate entire groups of NSEs on a regional scale. The paper first presents an overview of the methodology followed by an example. Some further discussion surrounding important considerations and future work are also highlighted.

EAL Rating (EAL)	Life Safety Index (IS-V)	Risk Rating
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 ≤ 7.0%	IS-V < 15%	F
EAL ≥ 7.0%		G

Fig. 2 – *Sismabonus* seismic risk classification scheme for buildings; the risk rating is the more critical of the EAL and IS-V ratings

2. Overview of risk classification methodology

2.1. Mean annual frequency of exceedance

For a given building, the seismic response with increasing intensity can be established from some kind of structural analysis procedure (e.g. incremental dynamic analysis, multiple-stripe analysis). This means that the relationship between structural demand, D, and seismic intensity, s, is known and is herein termed a *demand-intensity* model. Demand-intensity models essentially mean that for a given value of structural demand, D, the distribution of intensities required to exceed that in a building can be computed, as illustrated in Fig. 3. Knowing this intensity and the site hazard model determined from probabilistic seismic hazard analysis (PSHA), the mean annual frequency of exceeding (MAFE) that level of demand can be computed in a closed-form solution. If the MAFE is inverted, it gives the return period, T_R, in years of that demand being exceeded. This demand, D, can be a limit state deformation value (i.e. 0.5% storey drift) or the capacity, C, of a certain element in the structure; for example, a beam's chord rotation at yield or a NSE's first damage state, both of which have a median capacity and an associated dispersion (i.e. fragility function).

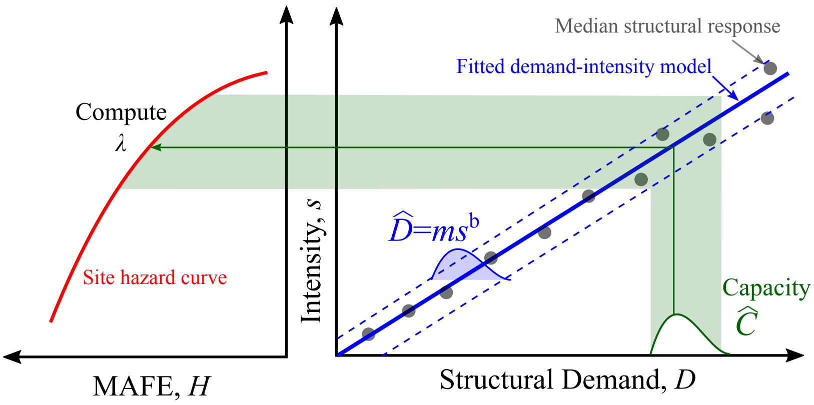

Fig. 3 – Illustration of MAFE computation for an NSE capacity, C, using a structure's demand-intensity model and site hazard model, where the uncertainty surrounding the capacity and the demand are explicitly considered [12] (Note: the symbol ^ denotes the median value)

The performance of an NSE can be quantified as the probability that the demand, D, exceeds the damage state capacity, C, of that NSE for a given intensity of shaking, s, described by Eq. (1). If the demand on an NSE being transmitted from a structure is described by a lognormal distribution and the capacity of the NSE (i.e. its fragility function) is defined similarly, then the MAFE can be computed in a single expression depending on which type of parameter the NSE is sensitive to (i.e. drift or acceleration). The MAFE of ground shaking intensity s is described by the site hazard curve, $H(s)$, determined from PSHA. When integrated with Eq. (1) for all intensities, it gives the MAFE that the NSE capacity is exceeded, as per Eq. (2). For the hazard, the quadratic relationship (Eq. (3)) can be used, where the coefficients k_0, k_1 and k_2 are fitted to the PSHA data.

$$P[D > C|s] \tag{1}$$

$$\lambda = \int_0^{+\infty} P[D > C|s]\,|\mathrm{d}H(s)| \tag{2}$$

$$H(s) = k_0 \exp(-k_1 \ln s - k_2 \ln^2 s) \tag{3}$$

2.2. Classification of performance

Based on either λ or T_R, a rating system (e.g. A+, A, B, C etc.) may be defined to classify the NSE performance for a given structural typology and site location. The input requirements for this would therefore be: 1) site location and a suitable hazard model; 2) structural typology to characterise its demand-intensity model required for that NSE; 3) fragility of non-structural element; and 4) decision framework to assign a risk rating. Using such an approach illustrated in Fig. 4, its output would be the MAFE for a given NSE, structural typology and location, which could then be used to quantify and classify the risk of NSEs. This would be similar to the *Sismabonus* risk classification system for buildings but explicitly for NSEs.

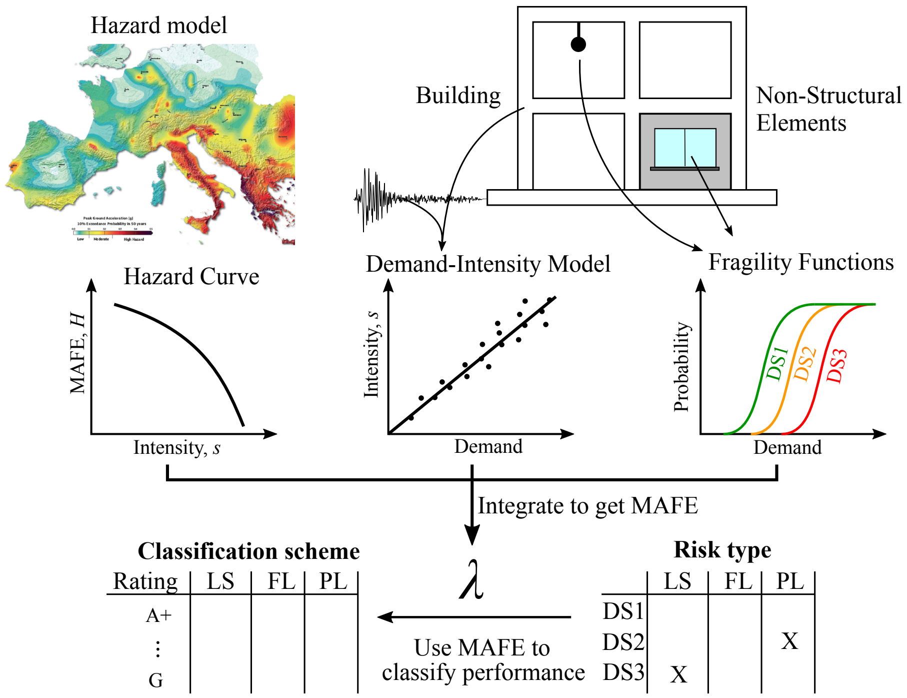

Fig. 4 – Illustration of risk quantification and classification for NSEs

A classification scheme for NSEs could focus much more on mitigating the immediate impacts and consequences due to the failure of certain NSEs on the building, its functionality and its occupants. FEMA E-74 describes a differentiation among NSEs and which type of risks they pose, which are summarised in Table 1. For each risk type, different levels of acceptable MAFE or return periods of failure could be assigned. For example, the life safety risk could be strictly controlled in buildings with a large concentration of people (e.g. a school or hospital building) but the functionality may be the primary issue to address in a warehouse building. Establishing these limits is not an easy task and collaborative research is needed to identify suitable values, but it is argued to be a much more thorough and meaningful way to classify and rank the performance of NSEs compared to more typical demand/capacity ratios that current codes employ.

Table 1. Types of risk for NSEs described in FEMA E-74 [13]

Type of Risk	Description	Example
Life safety (LS)	Could anyone be hurt by this NSE in an earthquake?	School building
Property loss (PL)	Could a large property loss result due to the loss of this NSE?	Warehouse
Functional loss (FL)	Could the loss of this NSE cause an outage or interruption to the functionality of this building?	Civil protection building

As a preliminary guide, Fig. 5 illustrates some example values of acceptable failure rates for the three different types of risks identified in FEMA E-74. It is noted that these values are not intended for immediate use but rather that illustrate what this framework could look like once suitable values are established. Each risk type starts off by having a minimum protection return period of 50 years (i.e. MAFE = 0.02) and varies linearly in logspace up to different maximum levels of protection, although it doesn't necessarily need to be. Based on these, a letter-based scheme can be developed to score the NSE being examined. Another task that must be performed for each NSE is to associate a risk type to each of the damage states. For example, the collapse of a ceiling system clearly poses a life safety risk and should be treated as such. However, loss of a piping system that provides water to a building would be considered a functionality risk, for example.

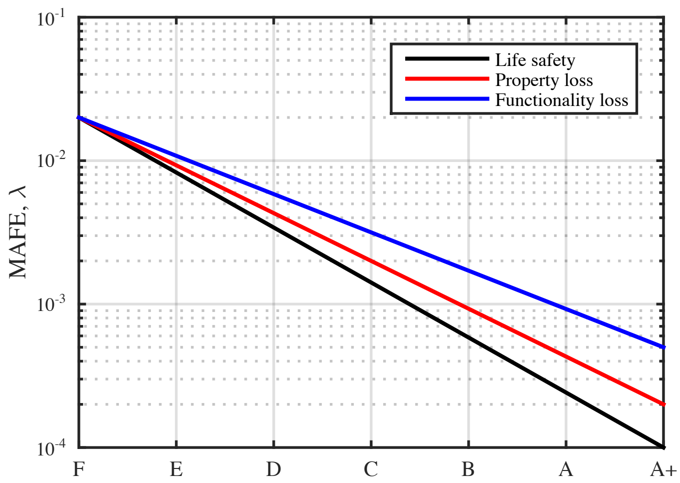

Fig. 5 – Hypothetical risk classification system for NSEs based on the type of risk

3. Quantification of MAFE

3.1. Storey drift-sensitive elements

The objective is to estimate the MAFE of a certain NSE damage state, whose fragility function is described by a lognormal distribution with median capacity η_C and dispersion β_C. In terms of demand, the median structural response of a building is predicted using a demand-intensity relationship represented as linear in logspace for storey drift. This relationship is described in Eq. (4), where θ_{max} represents the maximum peak storey drift (MPSD) along the building height in the direction of interest. The empirical coefficients m_θ and b_θ are determined from structural analysis or empirical relationships, depending on the characteristic of the building in question, and s is the intensity measure.

$$\theta_{max} \approx m_\theta s^{b_\theta} \tag{4}$$

Using such a demand-intensity model, Vamvatsikos [14] derived closed-form expressions to compute the MAFE for MPSD, λ_θ, given in Eq. (5) where the ϕ'_θ term is described by Eq. (6). The dispersion terms β_D and β_C represent the uncertainty in the structural demand and the NSE capacity, respectively, and may consist of both aleatory and epistemic sources. The function $H(\bullet)$ and the terms k_0, k_1 and k_2 are given by the hazard curve fit described in Eq. (3).

$$\lambda_\theta = \sqrt{\phi'_\theta} k_0^{1-\phi'_\theta} H\left(\left(\frac{\eta_C}{m_\theta}\right)^{\frac{1}{b_\theta}}\right)^{\phi'_\theta} \exp\left[\frac{k_1^2 \phi'_\theta}{2b_\theta^2}(\beta_D^2 + \beta_C^2)\right] \tag{5}$$

$$\phi'_\theta = \frac{1}{1 + \frac{2k_2}{b_\theta^2}(\beta_D^2 + \beta_C^2)} \tag{6}$$

3.2. Floor acceleration-sensitive elements

In the case of acceleration-sensitive elements, the objective is again to estimate the MAFE of a certain NSE damage state, whose fragility function is again described by a lognormal distribution with median capacity η_C and dispersion β_C. The maximum of the peak floor accelerations (MPFA), a_{max}, is a demand parameter typically used for acceleration-sensitive components. MPFA is a quantity that behaves differently to MPSD and begins to saturate with increasing intensity as a result of structural yielding. The result of this is that a single linear fit in logspace for the demand-intensity model is no longer sufficient over the entire range of structural response. To this end, O'Reilly and Monteiro [15] proposed a bilinear demand-intensity model described by Eq. (7), where s_{lim} represents the intensity at which the structure is expected to yield. Assuming first-mode dominated response, this limiting intensity may be estimated as the ratio between the base shear and modal mass if using spectral acceleration at the first mode period as an intensity measure. The coefficients $m_{a,lower}$, $m_{a,upper}$, $b_{a,lower}$ and $b_{a,upper}$ are again coefficients quantified from response analysis results, or similar, and are fitted to ensure that a continuous function over the interface intensity s_{lim} results.

$$a_{max} \approx \begin{cases} m_{a,lower} s^{b_{a,lower}}, & s < s_{lim} \\ m_{a,upper} s^{b_{a,upper}}, & s \geq s_{lim} \end{cases} \tag{7}$$

Using this bilinear demand-intensity model, the MAFE for MPFA, λ_a, was derived in a closed-form expression by O'Reilly and Monteiro [15] and described by Eq. (8). $F_{lower}(s)$ and $F_{upper}(s)$ are the lognormal cumulative density function values with corresponding mean values of μ_{lower} and μ_{upper} and standard deviations of σ_{lower} and σ_{upper}, respectively, which when using the respective coefficients in Eq. (7) are described by Eqs. (9) – (12).

$$\lambda_a = F_{lower}(s) G_{lower} + \left[1 - F_{upper}(s)\right] G_{upper} \tag{8}$$

$$\mu = \phi'_a \left(\frac{(\ln \eta_C - \ln m_a)}{b_a} - \frac{k_1(\beta_D^2 + \beta_C^2)}{b_a^2}\right) \tag{9}$$

$$\sigma = \frac{(\beta_D^2 + \beta_C^2)\sqrt{\phi'_a}}{b_a} \tag{10}$$

$$\phi'_a = \frac{1}{1 + \frac{2k_2}{b_a^2}(\beta_D^2 + \beta_C^2)} \tag{11}$$

$$G = \sqrt{\phi_a'} k_0^{1-\phi_a'} H \left(\left(\frac{\eta_C}{m_a} \right)^{\frac{1}{b_a}} \right)^{\phi_a'} \exp\left[\frac{k_1^2 \phi_a'}{2b_a^2} (\beta_D^2 + \beta_C^2) \right] \quad (12)$$

4. Example Application

An example of how the MAFE may be computed and the proposed risk classification utilised for a 4 storey RC moment frame building taken from [16] and examined in detail [12] is discussed here. Its dynamic behaviour was quantified using incremental dynamic analysis (IDA) and the results characterised by the median, 16% and 84% fractiles are plotted in Fig. 6. As shown, the seismic intensity measure, s, is chosen as the spectral acceleration at the first mode period of vibration of the structure, $Sa(T_1)$ and the demand-intensity model coefficients are described by O'Reilly and Calvi [2019] as: $m_\theta = 3.45$, $b_\theta = 1.03$, $m_{a,lower} = 2.18$, $m_{a,upper} = 1.19$, $b_{a,lower} = 1.01$, $b_{a,upper} = 0.61$ and the limiting intensity $s_{lim} = Sa_y(T_1) = 0.22$g. The building is situated in a location whose seismic hazard is characterised via the coefficients $k_0 = 7e\text{-}4$, $k_1 = 2.0$ and $k_2 = 0.3$.

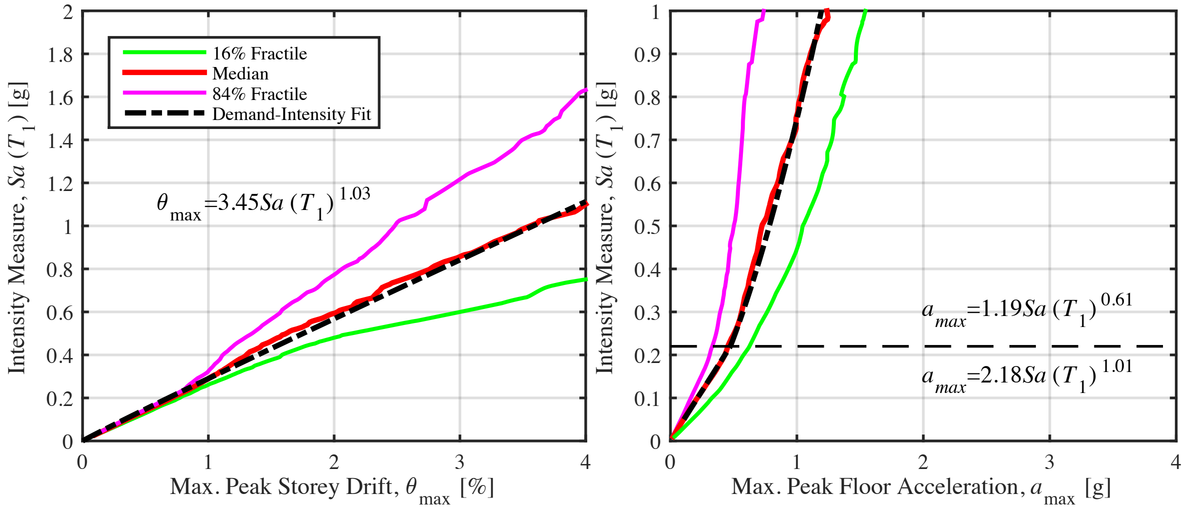

Fig. 6 – Illustration of the IDA results of a 4 storey RC frame structure for both MPSD and MPFA, where the fitted demand-intensity models are also shown

To evaluate the performance of NSEs in this particular building, two cases are considered: a drift-sensitive and an acceleration-sensitive NSE. For the first case, gypsum partitions with metal studs are considered and for the second case, a cooling tower is examined. The "significant damage" damage state of the partitions and the "loss of functionality" damage state of the cooling tower are analysed, which are both deemed "Functionality loss" risk types according to Fig. 5. Fragility functions for these two damage states are taken from FEMA P-58-3 [17] and are plotted in Fig. 7 along with their limit state median capacities η_C and dispersions β_C. Following the expressions outlined previously, the MAFE of the damage states is computed for the NSEs and is described in Table 2 and Table 3 with reference to the expressions used at each step. Lastly, the tentative classification scheme plotted in Fig. 5 is also utilised to assign a risk class.

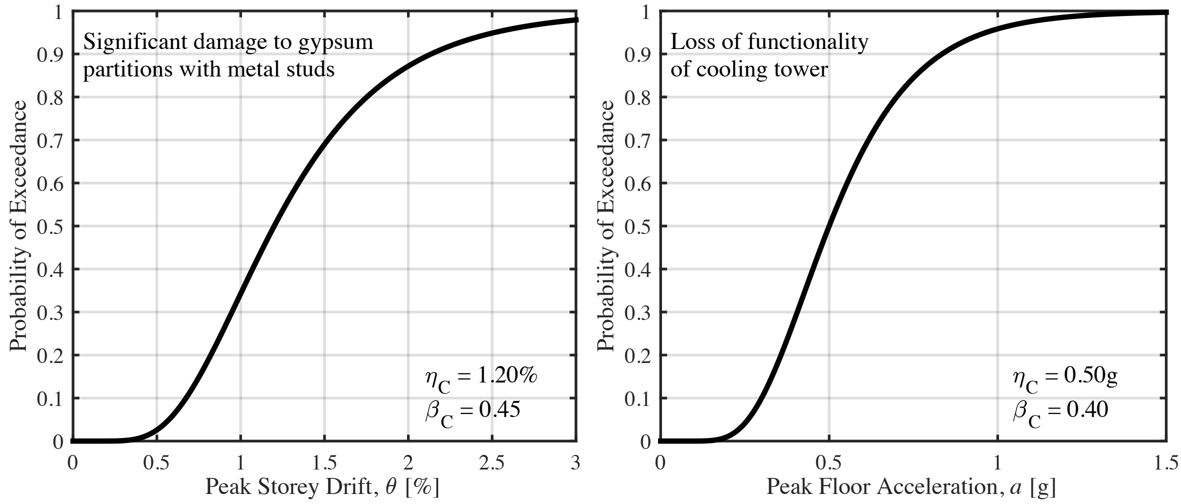

Fig. 7 – Illustration of the NSE fragility functions: gypsum partition (left) and cooling tower (right)

From the results shown in Table 2 and Table 3, it can be seen that the MAFE of particular NSE damage states located in certain buildings can be computed in a relatively simple manner. One of the main advantages of expressing the performance this way is that NSEs can be evaluated simultaneously and their relative risks compared. Additionally, the level of risk of a certain damage state is evaluated and quantified in a probabilistic manner. This means that the uncertainties present in the characterisation of both NSE and structural behaviour can be effectively propagated and taken into account in decision-making. This represents a marked improvement to current pass/fail methods for evaluation or quantifying NSE performance. Furthermore, this kind of quantification allows the relative risk to be managed more efficiently through the systematic reduction of the different NSE element MAFE, depending on which are deemed more critical, allowing prioritisation schemes to be easily developed. Lastly, the simplified means with which this methodology is implemented means that alternative NSE retrofitting solutions (e.g. inclusion of isolators underneath the cooling tower) simply means that the fragility information needs to be updated and the impact on reducing the MAFE can be examined.

5. Potential usage of a risk classification system for NSEs

5.1. Relevance in design, assessment and retrofitting

The previous sections have highlighted a means to compute the MAFE of an NSE damage state. The direct consideration of NSE performance in this manner may allow for more suitable decisions to be made in the design of new buildings and the retrofitting of existing ones. Furthermore, if an NSE manufacturer wishes to sell its products to a building owner using simple but meaningful language, this could be easily demonstrated using the proposed classification system. Discussing the increased resilience of the NSE to seismic shaking due to its reduced vulnerability (i.e. its fragility function shifts to the right) may not be so convincing to a building owner not familiar with the meaning of fragility functions. However, if a manufacturer were simply able to 'tag' their product as Class A, whereas another product would correspond to a Class D, the advantage would be much clearer.

Similar in the design of retrofits, where a building owner may discover that their building is not at a high risk of structural collapse but is prone to accumulating large economical losses. O'Reilly and Sullivan [18] demonstrated that in situations where collapse performance is satisfactory, the retrofitting of NSEs can have a much bigger effect on reducing the expected losses when compared to traditional structural interventions (which in some cases actually increased the losses due to excessive strengthening and stiffening). In this light, how are designers to know what kind of NSE retrofitting is required? If the proposed scheme were to be adopted and it is determined that the NSEs must all be improved to at least a Class B performance, for example, the increased resistance to storey drift or floor acceleration required from each NSE could be computed.

Table 2. Computation of the MAFE and risk classification for the significant damage limit state of the gypsum partitions with metal studs located in a 4 storey RC frame building

Description	Reference	Value(s)
Demand-intensity model	Eq. (4)	$m_\theta = 3.45$, $b_\theta = 1.03$, $\beta_D = 0.30$
Site hazard model	Eq. (3)	k_0 = 7e-4, $k_1 = 2.0$ and $k_2 = 0.3$
NSE fragility function	Fig. 7	$\eta_C = 1.2\%$, $\beta_C = 0.45$
MAFE	Eq. (6)	$\varphi'_\theta = 0.86$
	Eq. (4)	$Sa(T_1) = 0.36$g
	Eq. (3)	$H(Sa(T_1))$ = 3.97e-3
	Eq. (5)	λ_θ = 4.61e-3
Return period		$T_R = 217$ years
Rating	Fig. 5	D

Table 3. Computation of the MAFE and risk classification for the loss of functionality limit state of a cooling tower in a 4 storey RC frame building

Description	Reference	Value(s)
Demand-intensity model	Eq. (7)	$m_{a,lower} = 2.18$, $m_{a,upper} = 1.19$, $b_{a,lower} = 1.01$, $b_{a,upper} = 0.61$, $\beta_D = 0.30$
Site hazard model	Eq. (3)	k_0 = 7e-4, $k_1 = 2.0$ and $k_2 = 0.3$
NSE fragility function	Fig. 7	$\eta_C = 0.50$g, $\beta_C = 0.40$
MAFE	Eq. (11)	$\varphi'_{a,lower} = 0.87$, $\varphi'_{a,upper} = 0.71$
	Eq. (9)	$\mu_{lower} = -1.70$, $\mu_{upper} = -1.36$
	Eq. (10)	$\sigma_{lower} = 0.23$, $\sigma_{upper} = 0.35$
	Eq. (4)	$Sa(T_1)_{lower} = 0.23$g, $Sa(T_1)_{upper} = 0.24$g
	Eq. (3)	$H(Sa(T_1)_{lower})$ = 6.83e-3, $H(Sa(T_1)_{upper})$ = 6.55e-3
	Eq. (12)	G_{lower} = 7.30e-3, G_{upper} = 7.58e-3
		$F_{lower} = 0.79$, $F_{upper} = 0.33$
	Eq. (8)	λ_a = 1.08e-2
Return period		$T_R = 92$ years
Rating	Fig. 5	E

5.2. Implementation on a regional scale

In addition to focusing on a single structure like the example presented in Section 4, the proposed classification framework may also be extended to a regional scale. That is, if the hazard data for numerous locations in a given region are known and the demand-intensity model coefficients can be quantified for a range of building typologies, then the process outlined previously may be implemented. This way, the expected failure rate of a certain NSE across an entire region could be mapped.

An example of regional assessment is using the OpenQuake engine developed by the Global Earthquake Model (GEM) Foundation. In this type of regional study, more focus is given to the economic losses associated with damage to buildings than the performance of individual buildings or their elements themselves. This method works well for the assessment of entire regions and delivers on its goals to communicate risk on a larger scale to the relevant stakeholders and decision-makers. However, its extension to NSEs is a little problematic since it is not formulated in an overly convenient manner. It typically utilises a bilinear single degree of freedom (SDOF) oscillator representation of entire buildings and derives fragility functions based on these. No attention is given to acceleration-based damage states which are of undoubted importance in the assessment of NSEs. Therefore, this type of global approach may not be particularly well-suited to assessing individual types of NSEs. Instead of providing sets of fragility and consequence functions for each building typology, its demand-intensity model could be provided. This way the methodology described in this paper may be directly implemented to compute the MAFE of an NSE and may offer an improved estimate of performance over the SDOF oscillator approach.

6. Summary

A risk classification scheme for non-structural elements (NSEs) has been described. A methodology to quantify the performance of both storey drift-sensitive and floor acceleration-sensitive NSEs was described whereby the mean annual frequency of exceeding (MAFE) a given damage state is determined. This utilises information from seismic hazard analysis, structural analysis and also NSE behaviour to characterise the performance consistently, while at the same time incorporating the uncertainties involved to be in line with modern performance-based earthquake engineering. A classification scheme to rank the performance in a simplified manner similar to the seismic risk classification for buildings *Sismabonus* used in Italy was described. While a hypothetical example of what such a scheme may look like was discussed, future work is needed to identify what the acceptable performance limits for such risk types may be. An example implementation of the methodology was described for two types of NSE to illustrate its simplified nature. Lastly, the potential benefits of using this methodology for engineers and manufacturers were discussed in addition to its extension to a more regional level. It is viewed that this methodology may set forth a simple but robust framework within which NSE performance may be tackled in the name of improving overall building performance.

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