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Hazard-, Risk-, and Loss-based Seismic Design: Review and Proposal for A New Methodology

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Abstract: There exist three categories of seismic design procedure: hazard-, risk- and loss-based design. Hazard-based design procedures, like the simple equivalent lateral force (ELF) method, have a long history in earthquake engineering, however they have been shown to produce structures with inconsistent annual collapse probabilites. Risk-based procedures were developed to address this issue by using the mean annual frequency of collapse as design objective. Recently, loss-based deisgn procedures have been introduced which utilise not just the mean annual frequency of collapse as a performance objective but also the expected annual economic losses. These loss-based procedures are a promising new development in the field of earthquake engineering. This paper presents a review of a number of the hazard-, risk- and loss-based design procedures that are currently available in design codes and the literature. A concept for a new loss-based procedure, intended for use within the ELF framework, is proposed and the research developments required to realise this method are identified and discussed.

Keywords: Expected Annual Loss, Mean Annual Frequency of Collapse, Fragility Curves, Reference Peak Ground Acceleration,

1. Introduction

Procedures for the performance and loss assessment of structures have been the subject of intense development in the past couple of decades and engineers are able to estimate structural performance metrics such as annual probability of collapse or the expected annual losses (EAL) with a reasonable level of confidence. However, the procedures required for such analyses are often complex and need significant amounts of detailed information about the structure being assessed, such as exact member sizes, reinforcement requirements, inventories of damage components, and detailed seismic hazard data. What this means is that, although the current performance assessment procedures are accurate and provide reasonable estimates of building performance, they do not lend themselves well to implementation during the design phase, where informed estimates of building performance are of the most use. During design, engineers typically use simplified seismic design techniques for all but the most high-profile and complex structures.

Traditional code-specified seismic design techniques based on the uniform hazard concept, although producing safe structures, have been shown to result in designs with inconsistent performance/reliability (Silva et al. 2016). Recent research efforts have focussed on developing design procedures of varying complexity that aim to improve upon hazard-based design and target a uniform mean annual frequency of collapse (MAFC) (Luco et al. 2007, Silva et al. 2016, Žižimond and Dolšek (2019)) or drift hazard (Vamvatsikos and Aschheim 2016). It is possible for this target MAFC to be calibrated using an acceptable risk of human loss (Crowley et al. 2018; Silva et al. 2016). Building on the idea of risk-targeted design, a new concept for seismic design using seismic economic losses as the target design objective has been proposed (O'Reilly and Calvi (2019)). When widely adopted, this loss-based methodology has the potential to lead to new-building stocks that are robust and exhibit a well-defined level of structural performance and economic risk (Shahnazaryan and O'Reilly (2020)). Following a brief review of existing hazard-, risk-, and loss-based design philosophies and procedures, this paper proposes a conceptual methodology for a loss-based design procedure using the equivalent lateral force method. The procedure for the development of the proposed methodology will be described and the potential research challenges will be identified and discussed.

2. Review of Seismic Design Philosophies

2.1 Hazard-based Seismic Design

Hazard-based approaches focus on ensuring that the strength and deformation capacity of a structure are sufficient to resist the seismic forces imposed by a ground motion with a certain intensity, specified by an average return period (RTP), typically taken to be 475 years (i.e. ground motions with a probability of exceedance of 10% in 50 years). Force-based design procedures, such as the traditional equivalent lateral force (ELF) method (found in design codes such as Eurocode 8, ASCE-7 and NZS1170.5, amongst others), and displacement-based design procedures, such as direct displacement-based design (DDBD) (Priestley et al. 2007) are examples of hazard-based design procedures. In the ELF procedure the seismic forces are determined by multiplying the mass of the structure by the appropriate spectral acceleration, obtained from the code-defined design response spectrum. By contrast, in DDBD the seismic forces are determined from the displaced shape of the structure when a maximum target displacement is achieved. This target displacement is determined from the displacement response spectrum. Although fundamentally different in how they determine the seismic base shear, both of these methods can be considered hazard-based procedures because the seismic demands are based on response spectra defined by a ground motion with a reference peak ground acceleration (PGA) intensity with a specific return period.

Although structures designed using this hazard-based approach to seismic demand estimation are capable of meeting basic life-safety requirements, it has become apparent that structural performance (e.g. annual probability of collapse, P_c) can vary significantly between structures designed considering the same IM and the same RTP but located at sites with different shape hazard curves. For example, Silva et. al. (2016) showed in their study that the annual probability of collapse of structures in Italy, designed in accordance with EC8, varies between 1.3e-5 and 5e-5, a difference of a factor of 3.8. The variation in the observed collapse probabilities stems from a number of sources, with the most significant being the dynamic behaviour of different structural systems and the spatial variation of the seismic hazard (i.e. the shape of the site-specific hazard curve) (Silva et al. (2016)).

2.2 Risk-based Seismic Design

In an effort to address the observed variation in structural performance of buildings designed using the common hazard-based approaches, risk-based design methodologies have been proposed (e.g. Luco et al. (2007), Žižimond and Dolšek (2019)). In contrast to hazard-based design methods, where the structure is designed with a resistance/capacity greater than the demands induced by a ground motion with a specified RTP, risk-based procedures use seismic demands that have been calculated to provide a specific probability of collapse. The collapse risk of the structure, P_c, can be defined by the equation (Žižimond and Dolšek (2019)),

$$\lambda_C = \int_0^\infty P[C|IM] \cdot \left|\frac{dH(im)}{dim}\right| \cdot dim \tag{1}$$

where $H(im)$ is the site-specific hazard function and $P[C|IM]$ is the fragility curve that describes the probability of collapse of the structure for a given intensity, IM, conventionally assumed to be a lognormal cumulative distribution function. As illustrated by Equation 1, risk-based seismic demands are dependent on the assumed collapse performance of the structure for different levels of seismic intensity. By considering both the seismic hazard and building response characteristics in the determination of the seismic demands, risk-based design methods represent an improvement over the traditional hazard-based approaches. This risk-based approach is supported by the second generation of EC8, where Equation 1 has been adopted in Annex E to encourage the risk-based assessment of structures.

Perhaps the simplest risk-based design procedure is the risk-targeted spectra (RTS) proposed by Luco et al. (2007). RTS are developed by using the code specified equations for response spectra, but instead of using a hazard-based reference PGA, a risk-targeted reference PGA is determined by iteratively solving Equation 1 for a specific target MAFC. What makes this method particularly attractive is that it requires no changes to the fundamental ELF design procedure that is a corner stone of modern codes. RTS are currently employed in the loading code for the United States, ASCE-7. Recently, several studies have highlighted several issues with the RTS method that engineers should be aware of. First, a generic family of fragility curves is used to calculate the reference PGA that, apart from an increased dispersion, do not account for the differences in capacity reserve ratio (ratio between the median collapse intensity and the design PGA) or the inherent response characteristics of different structural systems, which leads to variations in the observed collapse risk (Gündel and Rapps (2019)). Secondly, the application of response modification or behaviour factors during the ELF design procedure (e.g. ASCE-7) can also result in uncontrolled levels of collapse risk as noted by Gikimprixis et al. (2019).

Building on this RTS procedure, Žižimond and Dolšek (2019) proposed a procedure for the determination of risk-targeted seismic actions (RTSA), in which the design spectral acceleration value is determined, using a similar RTS method to that proposed by Luco et al. (2007), and then applying a response modification factor, r_{NC}, based on the assumed structure ductility, inelastic deformation ratio and the desired yield force of the structure. The value of r_{NC} is initially assumed, and the collapse response of the structure is verified through an incremental dynamic analysis (IDA) of an equivalent SDOF system. If the desired collapse performance is not obtained with the assumed r_{NC}, through an iterative procedure the value of r_{NC} can be refined and the design improved. In a somewhat similar approach to RTSA, Vamvatsikos et al. (2020) proposed a methodology for the determination of the risk-targeted behaviour factors (RTBFs) which are intended to replace the typology specific q-factors and overstrength factors currently used in EC8. Like RTSA, the verification of the assumed behaviour factor is required through detailed nonlinear time-history analysis (NTLHA), however simple expressions are provided to estimate an improved RTBF after the first iteration, based on the observed structural performance. Vamvatsikos et al. (2020) highlighted that the combination of RTS and RTBF approaches to more reliably target a MAFC is a promising and open field of research.

Yield Frequency Spectra (YFS) (Vamvatsikos and Aschheim 2016) is a sophisticated design procedure that allows the consideration of multiple drift-based performance objectives during the initial design phase. By making use of the SPO2IDA to develop expected R-μ-T relationships for the proposed structure (Vamvatsikos and Cornell 2006), a series of drift hazard curves (i.e. the mean annual frequency of exceedance (MAFE) of a level of drift) can be constructed for a range of equivalent SDOF oscillators, characterised by different yield forces, C_y. The performance objectives are defined by target drifts and corresponding mean annual frequencies of exceedance. The lowest value of C_y, for which the MAFE values of the hazard curve are lower than the performance objectives is then used as the lateral design force of the structure. Although more complex to implement initially than either the RTS or RTSA methods, YFS has several significant benefits. First, unlike the RTS, this method is not affected by the introduction of the behaviour factors that modify the response of the structure as this is accounted for through the use of SPO2IDA. Secondly, no detailed IDA or other NLTHAs are required to verify the design or assumed factors, as is the case of the RTSA or RTBF methods.

It is clear from the selection of methods described in the previous paragraphs that there is no consensus on the best procedure for the risk-targeted design of buildings. The methods presented vary from the simple to the complex, however one thing that they have in common is that the performance objectives are always presented in terms of the MAFE of either collapse or a given limit state (or collection of limit states). The problem with using MAFE of exceedance as the only performance objective is that it can be difficult to communicate the level of performance of the building to decision makers or building owners in way that is relatable for them.

2.3 Loss-based Seismic Design

Following the Northridge Earthquake in 1996 it was obvious that it was not building collapse but reparable damage to structural elements, non-structural components and building contents that provided the largest portion of economic costs. To better understand the seismic performance of buildings and their economic vulnerability the PEER-PBEE performance and loss assessment methodology was developed (FEMA (2018)). A primary goal of this project was to develop a method for communicating structural performance and the economic risk associated with anticipated earthquake damage in a way that is easily understood by decision makers and building owners (FEMA (2018)). This resulted in economic variables such as the EAL, (the average yearly cost of repairing seismic damage) being adopted to describe building performance. The proposed methodology is extremely comprehensive and represents the state-of-the-art in terms of seismic performance assessment, however, due to its complexity and the requirement of many detailed non-linear structural analyses its application has been primarily limited to the assessment of existing structures or as a final design verification. Nevertheless, the introduction of the PEER-PBEE shifted the focus of earthquake engineers away from just thinking in terms of member forces and deformations and towards true performance-based seismic design.

Following in the footsteps of the PEER-PBEE framework, many simplified loss assessment methodologies have been proposed, however, to date, only a few studies have investigated using economic losses as a performance objective during the design phase. Calvi and O'Reilly (2019) proposed a methodology for the conceptual seismic design of buildings in which EAL is used as the primary performance objective. In this methodology the loss curve of the structure is approximated using a second-order closed-form expression similar to those used to fit seismic hazard curves and is anchored at three points: the economic losses incurred at the onset of seismic damage (high frequency/low intensity ground motions); losses incurred at the Ultimate Limit State (ULS)/collapse of the structure (low frequency/high intensity ground motions); and an intermediate Serviceability Limit State

(SLS). By specifying an acceptable level of economic loss ($L_{t,SLS}$) and an appropriate MAFE at for the SLS (λ_{SLS}) the loss curve can be defined for a specific EAL. Utilising storey loss functions, the maximum allowable drifts and accelerations at the SLS can be found, which subsequently limit the range of initial periods of the structure if the target loss level is to be respected. The design base shear is determined by using the ULS design acceleration-displacement response spectrum and displacement reduction factors based on structural ductility. Shahnazaryan and O'Reilly (2020) extended the original concept by considering the MAFC as a performance objective in addition to expected annual losses, effectively combining the performance objectives of Calvi and O'Reilly (2019) and the procedures described in Section 2.2. This modified methodology leverages the predictive power of the SPO2IDA tool to efficiently estimate the collapse performance of the conceptual designs without the need for extensive analysis. Comparisons by Shahnazaryan and O'Reilly (2020) with existing risk-based procedures showed that the proposed method was able to more consistently produce structures that exhibited the target MAFC. To help guide future development of loss-based design procedures Calvi et al. (2021) described proposals for the determination of suitable functions for the loss curves, methods for the inclusion of indirect losses into the methodology and further discussed the application of the loss-based methodology for both design and assessment of structures.

It is clear that this conceptual loss-based design methodology represents a significant advancement in the performance-based design of buildings. The idea of a loss-based performance objective is very attractive, because right from the start of the design phase the designer is able to communicate the expected seismic performance of the structure to the client in a meaningful way and the design can be tailored to suit the level of risk that the client is willing to accept. Additionally, loss-based design methods allow for clear communication of the trade-offs when choosing between high performance designs (lower economic losses / increased initial cost) and the minimum acceptable design (higher economic losses / lower initial costs). Another benefit of loss-based design is its transparency. The decision to update design norms is a primarily a political one, as changes, especially those relating to seismic demand, will have an economic impact on the entire building stock within a territory. Loss-based design is a useful tool for these discussions because it can provide a correlation between the change in seismic demands/requirements and the expected economic impacts.

3. Conceptual Methodology for Loss-Based Design

The concept for the proposed loss-based design procedure described herein has been formulated in such a way that it can be easily integrated into existing seismic design codes that use the ELF method, unlike the methods proposed by O'Reilly and Calvi (2019) and Shahnazaryan and O'Reilly (2020). However, similar to Shahnazaryan and O'Reilly (2020), the proposed methodology uses two design objectives to ensure adequate performance of the structure: the MAFC, λ_C; and an acceptable threshold for the EAL. The target λ_C is used to ensure adequate structural reliability against collapse (design for reliability), whilst the target EAL serves to keep the economic costs incurred due to seismic damage below an acceptable limit (design for loss).

Similar to the RTS procedure proposed by Luco et al. (2007), where a risk-targeted PGA, $a_{gr,risk}$, is used to anchor the design response spectrum used in the ELF design procedure, the procedures proposed in this paper adopts a loss-targeted PGA, $a_{gr,loss}$, to anchor the response spectrum. A proposed procedure for determining the loss-based reference PGA, $a_{gr,loss}$, to be used with the ELF design procedure is presented in the following section.

3.1 Derivation of the Loss-based Reference Peak Ground Acceleration

The novel contribution of this work is the introduction of a loss-based reference PGA that can be used to anchor the design spectrum used in the ELF method. The procedure for deriving an appropriate loss-based reference PGA, which draws on work on conceptual loss-based design by Calvi et al. (2021) and the numerous studies that develop RTS for collapse reliability (Silva et al. 2016, etc.), is summarised in Fig. 1.

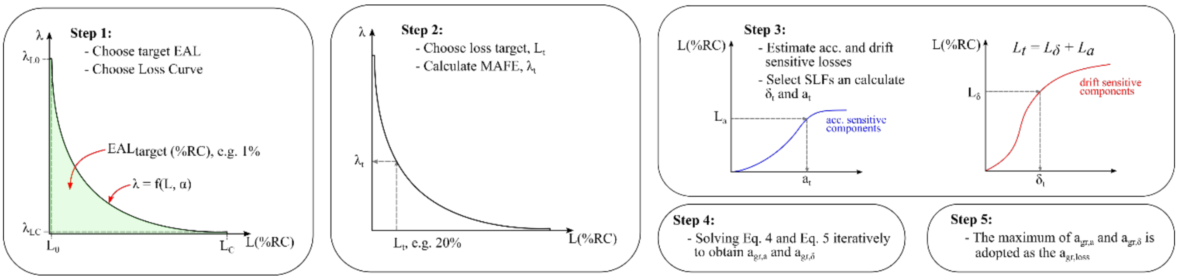

Fig. 1 – Summary of the procedure to calculate the loss-based reference PGA.

Initially, the proposed method follows the procedure described by Calvi et al. (2021). First, the designer chooses an acceptable threshold value for the EAL (expressed as a percentage of the building reconstruction costs, RC) and a suitable equation for the loss curve. Calvi et al. (2021) proposed,

$$\lambda_L = \lambda_{LC} + (\lambda_{L0} - \lambda_{LC}) \cdot \sin^{\alpha}\left(\cos^{-1}\left(\frac{L-L_0}{L_C-L_0}\right)^{\frac{1}{\alpha}}\right) \quad (3)$$

where, λ_L is the MAFE of a certain level of loss, L. λ_{L0} and λ_{LC} are the MAFE of the losses at the first on set of damage, L_0, and at collapse, L_C, respectively. These points are used to anchor the loss curve. The parameter α determines the shape of the loss curve between the anchor points and Calvi et al. (2021) has shown that for given combination of anchor points a simple relationship between EAL and α can be obtained. This α value then defines the loss-curve for the given anchor points and target EAL (Step 1 in Fig. 1).

Next, a target loss value is selected, L_t, and, using the loss curve defined previously, the corresponding target MAFE, λ_t, can be calculated (Step 2 in Fig. 1). Calvi et al. (2021) suggested that suitable value for L_t is approximately 20% RC, although the selection can be arbitrary. L_t, which is the sum of the losses associated with the structural elements, non-structural components and contents, can be divided into two components, L_δ and L_a, which represent the drift and acceleration sensitive losses, respectively.

In the third step, storey loss functions are employed to estimate the target inter-storey drift, δ_t, and target floor acceleration, a_t, that correspond to L_δ and L_a (Step 3 in Fig. 1). These loss functions differ for different building occupancy classes (e.g. office buildings, residential buildings, etc.).

Finally, in a procedure similar to the risk-targeted seismic design maps that determine a reference PGA to ensure adequate collapse reliability, λ_t, δ_t, and a_t are used to calculate the reference PGAs, $a_{gr,\delta}$ and $a_{gr,a}$, that correspond to the structure exceeding δ_t or a_t, respectively, with a MAFE of, λ_t (Step 4 in Fig. 1). This procedure iteratively solves the equations for the annual frequency of exceedance of a demand level (Jalayer and Cornell (2003)),

$$\lambda_t = \int P[\delta > \delta_t | a_{gr}] \left| \frac{dH(a_g)}{da_g} \right| da_g \tag{4}$$

$$\lambda_t = \int P[a > a_t | a_{gr}] \left| \frac{dH(a_g)}{da_g} \right| da_g \tag{5}$$

where $H(a_g)$ is the site-specific hazard curve using the PGA (a_g) as the intensity measure. $P[\delta > \delta_t|a_{gr}]$ and $P[a > a_t|a_{gr}]$ are the fragility curves representing the probability of the structure exceeding the target drift or the target acceleration, given that it was designed using a reference PGA, a_{gr}. It is probable that the values of $a_{gr,\delta}$ and $a_{gr,a}$ obtained from Equation 4 and Equation 5 will be different. Adopting the maximum of $a_{gr,\delta}$ and $a_{gr,a}$ as the loss-targeted reference PGA, $a_{gr,loss}$, will ensure that the EAL remains below the target threshold. Like the PGAs used in RTS, the loss-based PGA can be presented to practising engineers as a series of contour maps across a territory.

3.2 Proposed design procedure

The proposed general procedure for the seismic design of buildings, which utilises both $a_{gr,risk}$ and $a_{gr,loss}$ is summarised in Fig. 2.

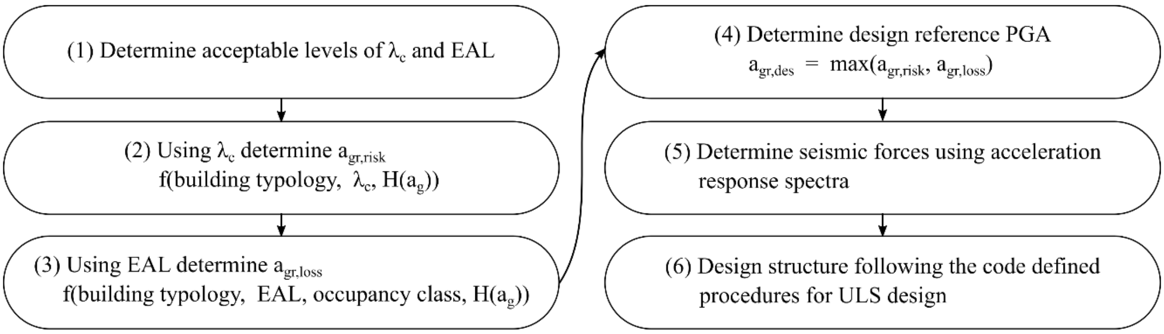

Fig. 2 – Summary of the proposed general seismic design procedure for buildings using the loss-based reference ground accelerations.

First, acceptable target values for the annual probability of collapse and EAL should be determined. These could either be minimum values specified in design codes or chosen by the designer, in collaboration with the client/decision maker. Next, a suitable value of $a_{gr,risk}$ is determined. This can be obtained by following the basic procedure adopted in previous studies, however, it is recommended that the values of $a_{gr,risk}$ are computed using typology-specific collapse fragility functions, in order to improve the estimation of the annual probability of collapse (Gündel and Rapps (2019)). In the third step the loss-targeted reference PGA is determined, following the procedure outlined in Section 3.1.

To make this methodology practical for practising engineers to implement, it is foreseen that a series of contours maps showing the spatial variation of the values of $a_{gr,risk}$ and $a_{gr,loss}$ would be precalculated so designers can easily read off the required reference PGA. A number of different maps would be required because each $a_{gr,risk}$ map is a function of the building typology, target P_C, and the seismic hazard. Similarly, the $a_{gr,loss}$ maps would be a function of the building typology, occupancy class, target EAL, and the seismic hazard.

In step four of the design procedure the design reference PGA, $a_{gr,des}$ is determined. Although $a_{gr,risk}$ and $a_{gr,loss}$ are reference PGAs that have been derived to meet different design objectives, only one can be used to design the structure. In this case the larger value is chosen to ensure that both design objectives are fulfilled, such that,

$$a_{gr,des} = \max\left(a_{gr,risk}, a_{gr,loss}\right) \tag{5}$$

Next, the seismic demands acting on the structure can be determined using the ELF method (Step 5). The design response spectrum can be calculated using the code defined equations and anchored using $a_{gr,des}$. Following the determination of the storey and member forces, the standard code procedures for the ultimate limit state (ULS) design of the structure can be followed to complete the design of the structure (Step 6).

4. Open Research Questions

The development of the proposed loss-based design method and the derivation of loss-targeted reference PGAs poses several questions that need to be addressed in order to facilitate the implementation of this methodology. Several of these challenges are presented and briefly discussed in the following paragraphs.

The first challenge is understanding how reliably structures designed using the RTS method achieve the target annual probability of collapse. It is well documented that the RTS method, as proposed by Luco et al. (2007), produces structures that still exhibit collapse probabilities that can vary significantly from the target (Gkimprixis et al. (2019), Žižimond and Dolšek (2019)). This variation can be primarily attributed to two factors as previously discussed; the use of a single ‘generic’ family of collapse fragility curves and the application of response modification/behaviour factors. One way of improving the predictive power of the RTS method would be to use building-typology-specific fragility curves (Gündel and Rapps (2019)) instead of the generic curve presented implemented by Luco et al. (2007). Following a similar procedure to Martins et al. (2018), families of fragility curves could be developed for different structural systems. If the predictive power cannot be sufficiently improved simply by using typology specific fragility curves then additional modifications to the structural design procedure will need to be implemented to ensure reliable behaviour. In Step 5 of the proposed design procedure (Fig. 2) the introduction of RTBF (Vamvatsikos (2020)) or reductions factors based on the RTSA method (Žižimond and Dolšek (2019)), in lieu of the typical q-factors used in EC8, could provide better control over the realised MAFC. Research efforts would need to be directed towards simplifying these existing methods so that they can be easily and accurately applied to a range of different structural systems during the initial design phase.

The majority of the open research lines are related to the determination of the loss-targeted reference PGA. These research lines can be broken down into two main categories:

implementation, which is related to the availability of information required to implement the methodology; and sensitivity, which is related to how sensitive the proposed method is to changes in some of the underlying assumptions. The two most obvious research lines that need to be addressed related to the implementation are the development of a suitable libraries of storey loss functions and drift and acceleration fragility curves applicable for a wide-range of combinations of structural typology and occupancy class. Available tools, such as those developed by Shahnazaryan and O'Reilly (2021), make the computation of the loss functions easier, however, the number loss curves required to allow the proposed loss-based design method applicable to a broad range of structures makes this a significant research undertaking. Similarly, a large number of fragility curves are required for use in Equation 4 and Equation 5 to calculate $a_{gr,loss}$. To be useful the fragility curves need to be provided for any target drift level for a structure designed using any value of reference PGA. Therefore, a worthy goal would be developing a series of equations that express the median of the drift/acceleration fragility curves of a structure as a function of the target drift/acceleration and $a_{gr,des}$. This is shown conceptually in Fig. 3.

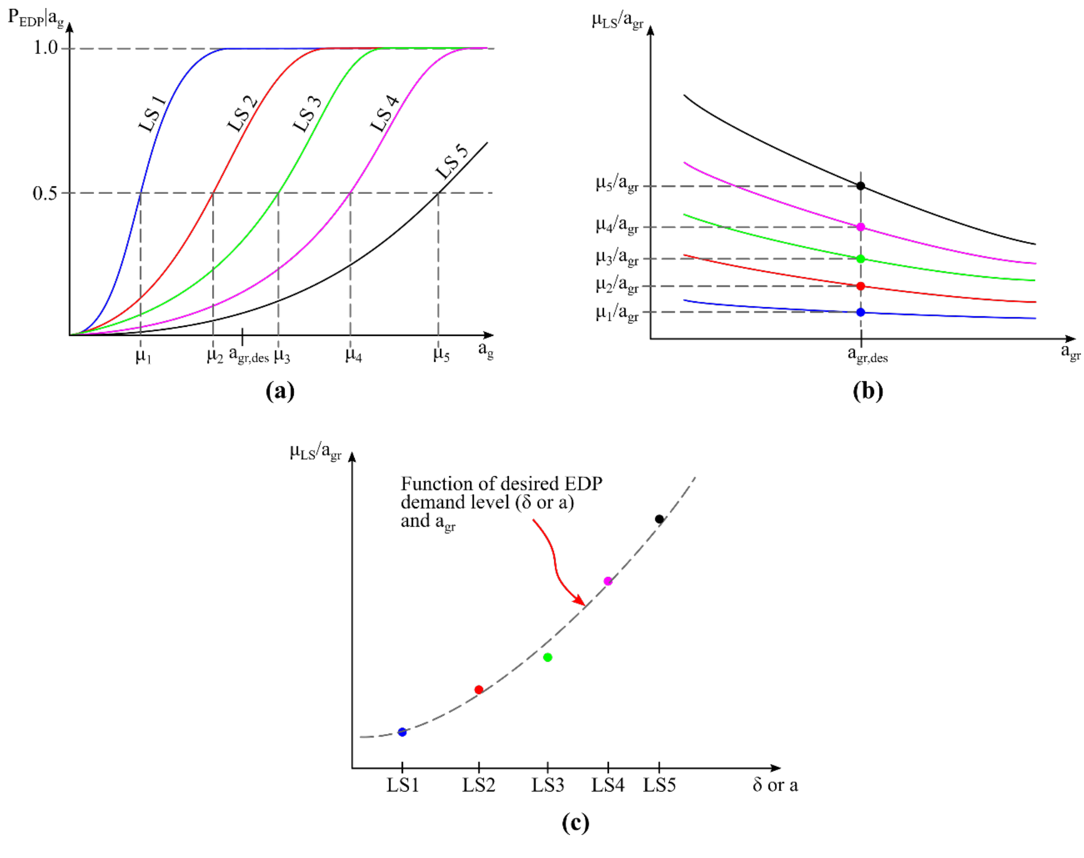

Fig. 3 – Determination of a families of typology-specific fragility curves for use in the proposed loss-based design framework. (a) A set of fragility curves for 5 different levels of engineering demand parameters (EDPs) for a building designed using a specific reference PGA, $a_{gr,des}$. (b) A potential relationship between the median values of the fragility curves and $a_{gr,des}$. (c) An equation can be formulated for the median of the fragility curve for any EDP value.

In terms of the sensitivity of the proposed method, the major lines of investigation would likely focus on how sensitive the loss-targeted reference PGA is to: variations in the values used to anchor the loss curve (Equation 3); the chosen combination of target loss, L_t and the corresponding annual probability of occurrence, P_t; and the shape of the loss curve for different building typologies and occupancy classes.

5. Conclusions

This paper has provided a summary of three different seismic design philosophies – hazard-, risk-, and loss-based design – and provided a brief review of several design methods that follow one or another of these philosophies. The novel contribution of this work was the proposal of methodology for simplified loss-based design that can be used with the simplified equivalent lateral force (ELF) method. The proposed method requires two design objectives to be set; the target mean annual frequency of collapse and an acceptable threshold for the expected annual loss. For each of these design objectives a reference peak ground acceleration can be determined, and the larger value is used to anchor the response spectrum used in the ELF method. A number of open research questions related to the implementation and sensitivity of the proposed method were identified and briefly discussed. The proposed methodology has the potential to make the loss-based design procedures easy to implement helps to improve the consistency of performance of the new building stock.

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