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Current and contemporary seismic design methods: a comparative review

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Abstract: With the introduction of performance-based earthquake engineering (PBEE), engineers have strived to relate building performance to different seismic hazard levels. This has been traditionally done using several intensities, or return periods, of seismic shaking to compute and verify the base shear force (and displacements) a structure is anticipated to withstand. In recent years, risk-oriented metrics like expected annual loss (EAL) and mean annual frequency of collapse (MAFC) have become prominent but tend to be limited to seismic assessment and evaluation rather than design and rehabilitation. This article reviews these traditional approaches available in most design codes to computing seismic design forces, quantifying performance and compares them with other contemporary approaches available in the literature. It aims to serve as a reference point from which designers can clearly see the differences, pros and cons and also underlying design philosophies and goals that they each follow to ultimately strive towards improving our current implementations of PBEE.

Keywords: PBEE; design methods; risk; loss; collapse.

1. Introduction

In recent years, earthquake engineers have worked to reduce damage to structural and non-structural elements in frequent low-intensity earthquakes and prevent collapse in rare high-intensity earthquakes. Following the economic impact of the 1994 Northridge earthquake in the US, largely due to the extensive damage and the overall disruption caused, an immediate shift was needed in defining building performance. Conventional objectives focusing on life safety and collapse prevention of buildings were not enough for acceptable building performance. This change materialised with the introduction of performance-based earthquake engineering (PBEE) during the latter half of the 1990s in the Vision 2000 framework (SEAOC 1995). It related desired building performance to various seismic hazard levels via the definition of limit states or performance levels. These were termed fully operational, operational, life-safe, and near-collapse, corresponding to hazard levels of frequent, occasional, rare, and very rare events, respectively.

In subsequent years, a probabilistic framework was developed and set the basis for what is known as the Pacific Earthquake Engineering Research (PEER) Centre PBEE methodology (Cornell and Krawinkler 2000). It quantifies the mean annual frequency of exceedance (MAFE), or failure, of a limit state, λ_f, by integrating the probability of failure for a chosen intensity measure (IM), $P[f|IM=im]$, with the site hazard curve, $H(im)$, as follows (Cornell et al. 2002):

$$\lambda_f = \int_{0}^{+\infty} P[f|IM = im]|dH(im)| \quad (1)$$

This modernised approach quantifies the building performance in an overall risk sense and is flexible in its definition of failure, allowing consistent consideration across all pertinent limit states (e.g., onset of structural/non-structural damage and collapse). Therefore, the overall performance of the building can be quantified via more meaningful metrics to building owners or stakeholders (e.g., casualties, economic losses, anticipated downtime). Due to the probabilistic nature of the framework and its computationally expensive implementation in certain situations, it has been largely popular within academic research or specialised reports (FEMA 2012; CNR 2014) rather than widespread code implementation for practitioners to use. Furthermore, given the nature of the framework, it has been predominantly developed for the assessment of existing buildings as opposed to the design of new ones.

This article reviews risk-targeted design methods proposed in the literature along with current code-based approaches. It first describes the general approaches followed before comparing them based on a series of criteria related to design objectives, ease of implementation and how PBEE-compatible, in the modern context, they really are. It is hoped that from this comparative discussion, practitioners can see the principal differences between methods and also appreciate the advantages and improvements offered via contemporary methods.

2. Seismic design of structures

2.1. Existing design code approaches

Current seismic design codes primarily focus on ensuring the life safety of building occupants by avoiding structural collapse. Additionally, performance at frequent levels of ground shaking has to be checked and verified. These are termed the *no-collapse requirement* and *damage limitation requirement* in the current version of Eurocode 8 (EC8) (CEN 2004) and are implemented at ground shaking return periods of 475 and 95 years, respectively, with possible modifications to account for building importance class. New Zealand's NZS1170 (2004) defines two limits states, termed as *serviceability* and *ultimate* with design return periods of 25 and 500 years, respectively, with the possibility of modification for different importance classes similar to EC8. A slightly modified approach is outlined in the recently revised design code in the US, ASCE 7-16 (2016), where the building is designed using a fraction of the maximum considered event (MCE) as input, which is determined from a series of risk-targeted hazard maps developed for a target collapse risk of 1% in 50 years. The design method employed in seismic design codes follows what may be referred to as force-based design (FBD). It calculates a design base shear force from a reduced elastic spectrum using either the equivalent lateral force (ELF) method or response spectrum method of analysis (RSMA). Despite seismic codes having the option to use non-linear numerical models for static pushover (SPO) analysis or non-linear response history analysis (NLRHA) with a set of suitable ground motion records, these approaches may be deemed too computationally expensive at times and not always implemented given the simpler linear-static options available.

While FBD boasts an attractive simplicity, Priestley (2003) and others pointed out several shortcomings. The use of displacement-based design (DBD) was thus advocated, where deformation demands in the individual elements drive the design process, culminating in the development of the direct displacement-based design (DDBD) method (Priestley, Calvi, and

Kowalsky 2007a) and other similar methods (Sullivan et al. 2003). One of the principal arguments by Priestley *et al.* (2007a) was that it was not reasonable to quantify the expected ductility and spectral demand reduction for different structural configurations via unique behaviour factors and proposed employing a ductility and typology-dependant spectral reduction. Hence, the idea that *one-fits all* solutions could be used for design were found to be ill-conceived and the actual performance of structures depends on a more detailed consideration of behaviour.

Both FBD and DBD methods can be good approximations for the initial seismic design of structures. However, neither explicitly quantify the structural performance in a manner that may be considered as having fully satisfied the goals of modern PBEE (i.e., the PEER PBEE methodology). This means that the actual performance of structures designed using these methods is not expected to be risk-consistent (i.e., the annual probability of it exceeding a certain performance threshold is not accurately known or consistent among different structures), and building performance parameters like collapse risk, expected economic losses and downtime do not feature in the design process. A recent initiative in Italy (Iervolino, Spillatura, and Bazzurro 2018) has shown that buildings designed according to the Italian national code (NTC 2018), which is similar to EC8, do not exhibit the same level of collapse safety when evaluated extensively, with large variations observed between different structural typologies and configurations. These FBD and DBD methods' design solutions may be refined and modified to become more in-line with risk-based objectives, as discussed in O'Reilly and Calvi (2020), or the behaviour factors adopted for different structural typologies may be adjusted and refined (Vamvatsikos et al. 2020), for example. Nevertheless, the fundamental issue of modern PBEE not being at the core of these classical methods remains.

2.2. Recent risk-targeted approaches

Over the years, different design methods aimed at risk-targeting have been developed and are widely accepted to eventually be prescribed and recommended in future design codes (Fajfar 2018; Vamvatsikos, Kazantzi, and Aschheim 2016). The US has already implemented criteria in the seismic design code ASCE 7-16 (2016) and FEMA P-750 (2009), and the new draft version of EC8 (CEN 2018) will include an informative annex on the probabilistic verification of structures. Any risk-targeted approach aims to control the risk of exceeding a limit state related to the performance of the building. The concept of risk-targeted behaviour factors (RTBF) was developed based on the work of Cornell (1996) and others, whereby behaviour factors are adjusted and revamped using more risk-consistent approaches. Procedures like FEMA P695 (ATC 2009) and recently by Vamvatsikos *et al.* (2020) outlined such approaches. Luco *et al.* (2007) introduced the concept of a risk-targeted design spectra to ensure uniform collapse risk for structures in the US. Douglas *et al.* (2013) and Silva *et al.* (2016) explored the extension of such an approach to Europe. Vamvatsikos and Aschheim (2016) introduced the yield frequency spectra (YFS) as a design aid to link the MAFE of any displacement or ductility-based parameter with the system design strength. Additionally, Žižmond and Dolšek (2019) introduced the risk-targeted seismic action method to be integrated with the current FBD procedures in EC8. Krawinkler *et al.* (2006) also introduced an early iterative approach, where effective structural systems are selected and sized and the performance of structural and non-structural elements and contents is evaluated for each. This approach utilises acceptable loss and collapse risk for decision-making to intuitively aid designers when implementing the PEER PBEE framework in design. These aforementioned studies are not intended to be an exhaustive list of available methods but rather some of the noteworthy proposals to integrate modern PBEE in seismic design.

2.3. Integrated performance-based seismic design

A novel conceptual seismic design framework that employs expected annual loss (EAL) as a design metric and requires very little building structure information at the design outset was initially developed by O'Reilly and Calvi (2019) and has been more recently formalised by Shahnazaryan and O'Reilly (2021) as integrated performance-based seismic design (IPBSD). It centres around defining a limiting value of EAL and identifying structural solutions through simplified hand calculations. Several assumptions were made to relate the performance objectives to a design solution space, which serves as an initial screening before detailing the structural members. Storey loss functions (SLFs) are used to relate expected loss ratios (ELRs, y) to engineering demand parameters (EDPs).

The IPBSD framework uses mean annual frequency of collapse (MAFC), λ_c, to directly ensure an acceptable level of collapse safety and an EAL limit, $\lambda_{y,limit}$, to mitigate excessive monetary losses in a building. Both are set by the designer based on the desired building performance. The target MAFC, $\lambda_{c,target}$, is set and used to limit the actual λ_c described by:

$$\lambda_c = \int_0^{+\infty} P[C|Sa(T)]|dH(Sa(T))| \le \lambda_{c,target} \tag{2}$$

and the $\lambda_{y,limit}$ limits the λ_y described by:

$$\lambda_y = \int_0^{+\infty} E[y]|dH| \le \lambda_{y,limit} \tag{3}$$

This integrated consideration of building performance in a risk-consistent manner represents a positive step for future revisions of design codes in line with the goals of modern PBEE.

3. Discussion of performance-based seismic design methods

With the brief overview of some of the currently available seismic design methods given in Section 2, a critical discussion is provided here. Figure 1 shows several design methods with the following abbreviations: IPBSD proposed by Shahnazaryan and O'Reilly (2021); FBD present in many seismic design codes (CEN 2004; NTC 2018; ASCE 7-16 2016; NZS 1170.5:2004 2004); DDBD outlined by Priestley *et al.* (2007b); RTBF described by Cornell (1996), amongst others; conceptual performance-based design (CPBD) proposed by Krawinkler *et al.* (2006); risk-targeted spectra (RTS) proposed by Luco *et al.* (2007); YFS proposed by Vamvatsikos and Aschheim (2016); and the risk-targeted seismic action (RTSA) method comprising both the direct (D) and indirect (I) approaches by Žižmond and Dolšek (2019).

The rows of Figure 1 list several categories common to each seismic design method. These are abbreviated and described as follows in the subsequent subsections: performance objective(s) (PO), which describe the primary quantity that each design method targets, limits or bases itself upon; seismic hazard (H) definition, meaning how seismicity is characterised in the design process; non-linearity (NL) meaning how ductile structural behaviour is accounted for to adequately determine a suitable set of reduced design forces; relative difficulty and directness (DD) meaning how difficult (i.e. is the method feasible with just a spreadsheet or is extensive NLRHA required?) and direct (i.e. are multiple iterations required to obtain the final solution?) the method is; (PBEE) whether or not the method is risk-consistent; and the flexibility (FLX) of the method meaning how easy is it to tailor the design targets beyond what it has been developed for so far.

	IPBSD	FBD	DDBD	RTBF	CPBD	RTS	YFS	RTSA-D	RTSA-I
PO	λ_c λ_y	$E[D \mid T_R]$ $E[R \mid T_R]$	$E[D \mid T_R]$	CMR λ_c	$E[L \mid T_R]$ $P[C \mid T_R]$	λ_c	λ_θ λ_μ	λ_c	λ_c
H	$H(Sa(T))$	UHS	UHS	UHS $H(AvgSa)$	$H(Sa(T_1))$	UHS	$H(Sa(T_1))$	$H(Sa(T_1))$	$H(Sa(T_1))$ & UHS
NL	Assume μ and q_s and get q_μ from SPO2IDA	Traditional q factors	Equivalent viscous damping	Calibrated q factors	NLRHA	Traditional q factors	SPO2IDA	Assume r_s and μ_{NC} and calculate C_1 from IDA	Assume r_s and μ_{NC} and calculate C_1 from IDA (Equivalent q factor)
DD	Moderate	Easy	Easy	Easy	Very Extensive	Easy	Moderate	Extensive	Extensive
FLX	Flexible	Limited	Flexible	Limited	Flexible	Limited	Flexible	Flexible	Flexible
PBEE	Yes	No	No	Yes	Yes	No	Yes	Yes	Yes

Figure 1. Comparison of key similarities and differences of available seismic design methods.

3.1. Performance Objectives

The first comparative point concerns the POs. Beginning with FBD, the PO is related to the expected (or average) values of displacement, D, and lateral resistance, R, at specified return period, T_R, intensities. This requires a designer to ensure sufficient lateral strength at very rare T_R events, whilst limiting the expected displacement at frequent T_R events. DDBD follows a similar approach whereby the expected level of displacement demand at multiple T_R levels is used. This is quite typical of design codes, whereby a series of intensity-based checks with corresponding limit states are stipulated for practitioners to follow and verify. This essentially stemmed from the early interpretation of PBEE in Vision 2000 (SEAOC 1995).

As research grew on probabilistic-related aspects, it became clear that such an intensity-based approach may not be entirely appropriate for modern PBEE (Günay and Mosalam 2013) and structures designed this way did not provide the consistent level of safety they were perceived to have (Iervolino, Spillatura, and Bazzurro 2018). This led to developments on how these approaches may be improved but maintaining the same intensity-based approach familiar to practitioners. RTS, RTBF and RTSA-I are examples of such developments, where some *behind the scenes* adjustments are made to maintain the familiar intensity-based approach via a UHS while seeking to maintain risk-consistency among designs. They typically have collapse safety as their PO but differ slightly in their definitions of it. For example, to identify suitable behaviour factors to reduce the UHS in design, FEMA P-695 (ATC 2009) employs a collapse margin ratio (CMR), whereas a recent proposal by Vamvatsikos *et al.* (2020) for Europe employed λ_c.

YFS provides a way to identify structures that can limit the MAFE of deformation-based quantities like storey drift, θ, or ductility, μ. CPBD was a proposal that was in some ways ahead of its time as many of the tools needed to feasibly implement it were either not available, or yet to be developed. It discussed using an array of POs in its formulation and made an effort to illustrate these quantities for designers to understand. Further development of this approach by Zareian and Krawinkler (2012) utilised a storey-based approach with POs being defined as expected losses and collapse probabilities at specified intensities. This is one of the few methods that has attempted to directly incorporate economic losses into its formulation, although the manner in which it was framed appeared rather tough to practically implement at the time. The last is the IPBSD approach where the POs are the λ_c and the λ_y to target a certain collapse risk but also to limit the expected economic losses over all intensities. It is seen that the collapse risk objective is in line with other methods but the relatively simple integration of EAL as a design variable makes it an attractive option. This was a key point highlighted by Krawinkler *et al.* (Krawinkler et al. 2006), stating that performance-based designs are not readily condensable to a single design parameter but multiple parameters that affect different facets of response; for example, should the building possess insufficient strength and ductility, its collapse safety may be inadequate, whereas should it be too flexible, it may accumulate excessive drift-sensitive loss at low T_R events, but at the same time potentially accumulate too much acceleration-sensitive if too stiff, as demonstrated in Shahnazaryan et al. (2022). It was for this reason that O'Reilly and Calvi (2019) introduced the restriction of the initial period range and the subsequent identification of sufficient lateral strength and ductility.

3.2. Characterisation of seismic hazard

The next broad comparison is the manner in which they define seismic hazard. Traditional methods like FBD and DDBD rely on the use of a UHS at specified T_R levels. These UHS are anchored to some level of ground shaking computed using PSHA. In the case of EC8, PGA on rock is used and a predefined shape for all other periods at that T_R is fitted. It should be noted that while the use of specific T_R levels may not be ideal, neither is anchoring the shape of the entire design spectrum to a single parameter like PGA. The main problem with using a UHS is that in order to make the resulting design solutions risk-consistent, they need to either have some modifications made in how they are utilised or how they are defined. For example, RTS attempts to define the anchoring value of a UHS whereas RTSA-I instead modifies how the force reduction is introduced.

Alternatively, there is the use of seismic hazard curves determined from suitable PSHA, and are generically defined as $H(IM)$, noting that different IMs may be used. The most common hazard curve definition is the spectral acceleration at the first mode period of vibration of the structure, $H(Sa(T_1))$, which is employed by YFS, RTSA-D, RTSA-I and also IPBSD. The proposed method utilises several hazard curves defined within a range of feasible periods of vibration and not one specific value giving a degree of flexibility of final structural configuration when identified and sized. Other methods focus on the identification of a singular T_1 assumption for design which needs to be then iterated should the actual value not match.

3.3. Accounting for non-linear structural behaviour

In terms of how each method deals with non-linearity, FBD uses the traditional approach of behaviour factors for each structural system whereas other methods like RTBF have attempted to correct the definition of these to be more risk-consistent. However, the underlying assumption of a single force reduction factor for certain typologies remains. RTS as defined in ASCE 7-16 (2016) also utilises force reduction factors but as pointed out by Gkimprixis *et al.* (2019), this use of traditional behaviour factors means that the risk-consistency breaks down in this implementation of RTS. The RTBF approach attempts to rectify this inconsistency through appropriate behaviour factor calibration. DDBD utilises the concept of equivalent viscous damping, which is somewhat similar to behaviour factors but different because the spectral reduction is a function of the expected ductility demand rather than a fixed value. CPBD utilised a rather strenuous approach of multiple NLRHA for identification of suitable designs. The RTSA methods proposed by Žižmond and Dolšek (2019) account for non-linearity by assuming a set of values for the expected ductility capacity at near collapse, μ_{NC}, and overstrength of the structure, r_s, which are later verified for the subsequent design and iterated if needed. An additional C_1 parameter is also computed via an IDA analysis on an equivalent SDOF oscillator. It is worth noting that for the RTSA-I method, Žižmond and Dolšek (2019) describe how an equivalent risk-consistent behaviour factor may be identified, highlighting the link between it and other methods discussed here. To circumvent the use of assumed values for force reduction and subsequent verification, YFS and the proposed IPBSD method both utilise the SPO2IDA tool (Vamvatsikos and Cornell 2005) to compute the force reduction distribution directly. This tool relates the distribution of dynamic behaviour to the expected backbone shape of the structure using an extensive library of empirical coefficients calibrated using NLRHA. This has the advantage of allowing the dynamic behaviour to be estimated with a high degree of accuracy prior to designing the structure without any numerical analysis.

3.4. Ease of implementation

Regarding the relative difficulty and directness of each method, a generic ranking has been provided based on the authors' subjective opinion. Due to their direct nature and no essential requirement to iterate design solutions or conduct extensive dynamic verifications, the FBD, DDBD, RTBF and RTS methods are ranked as easy methods to implement. The CPBD method is ranked as very extensive due to the sheer amount of analysis required to implement it. The YFS and IPBSD methods are ranked as moderate as they do not require any dynamic analysis to implement. If the designer is confident in SPO2IDA tool's ability to characterise the dynamic behaviour of the structure, then no great difficulty is encountered. Small iterations may be needed to refine the solution, with some being refined to a spreadsheet whereas others require pushover analysis of numerical models. The RTSA methods are denoted as extensive by requiring an IDA on an SDOF oscillator to determine one of the design parameters. Designs may take a few iterations, with full numerical models being required. The authors of this approach have, to their credit, provided ample parametric studies and practical guidance for designers (Sinković, Brozovič, and Dolšek 2016) on how to tackle this aspect and good initial assumptions can easily be made, still making it an attractive option.

3.5. Method flexibility

In terms of flexibility of tailoring the design targets, the methods using behaviour factors (FBD and RTBF) are relatively limited since their performance is inherently linked to the assumption made in the derivation of the behaviour factor and no end-control is left to the designer. DDBD's use of equivalent viscous damping makes it somewhat more flexible as it allows designers to tailor their intensity-based drift limitations. The assumptions needed to derive RTS have been discussed by Gkimprixis *et al.* (2019) to not be without their difficulties as to how the general method ought to be employed and the spectra derived with different studies advocating different anchoring values of the parameter X (Douglas, Ulrich, and Negulescu 2013; Silva, Crowley, and Bazzurro 2016). All other methods are deemed as flexible as they let designers choose and tailor their specific design targets, increasing their appeal.

3.6. PBEE compatibility

Lastly, Figure 1 categorises the different methods as being PBEE-compliant or not. While this is not a new discussion (e.g. Vamvatsikos, Kazantzi, and Aschheim 2016), it is included here for completeness. Unsurprisingly, neither FBD nor DDBD meet modern PBEE goals, at least without some additional verifications (e.g. O'Reilly and Calvi 2020). Again, RTS fails this categorisation not because of a conceptual flaw but rather in how it has come to be implemented, as discussed by Gkimprixis *et al.* (2019). The other methods, including the proposed IPBSD, are all seen to be PBEE-compliant as their formulations directly incorporate the use of risk-oriented metrics implemented consistently.

4. Summary

This paper has presented a review of different design methods typically found in current design codes and guidelines in addition to more contemporary methods available in the literature. It presented a brief overview of the methods followed by a detailed discussion into how they address different categories of desirability as a seismic design approach. These were first related to the performance objectives used in design, how the seismic hazard characterisation is quantified to be used in design and how the expected non-linear behaviour of the structures can be handled. It then looked at each methods' difficulty to implement and overall directness (i.e., would iterations of the initial design be required?) followed by its flexibility in terms of how it can be modified to address different kinds of performance objectives according to a client's needs. Lastly, the extent to which each method satisfies what is now widely accepted as performance-based earthquake engineering was assessed.

Overall, it was seen how current design methods, such as those found in many design codes, deal with design without adequately accounting for the probabilistic nature of both seismic design input and structural response. More contemporary risk-consistent seismic design approaches are available; however, the willingness to adopt such approaches in future guidelines remains to be seen as their superiority in terms of the categories evaluated here should be abundantly clear.

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