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Risk and loss mitigation in seismic design: a review of current methods and future directions

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ABSTRACT

Under the broad scope of effective risk management, an essential part of earthquake engineering is the availability of tools to tackle the issue. From a decision-making and portfolio management viewpoint, it is desirable to engineer structures for a predefined level of safety, quantifiable through risk communication and insurance terminology. This paper reviews methods available for the seismic design of new and retrofit of existing building structures. Special attention is paid to the performance metrics being used and how these fit in with the broader scope of risk management. Comparisons with existing methods currently used in building codes are examined and shown to fall somewhat short of ensuring uniform risk societies. Some recent additions in the literature explicitly tackling the collapse safety of structures are shown to improve building codes, with a recent addition integrating annual collapse risk and economic losses as design targets also being considered. While having methods that allow engineers to design structures to respect thresholds of annual collapse risk and average annual losses is a clear development, suitable targets to be used in practice are also needed. Here, input from the insurance industry (and broader society) on what target performance parameters should be can enter the discussion. It is envisaged that by bringing these two aspects closer together through discussion and collaboration, engineers and decision-makers can begin to deliver the building structures appropriate for a more risk-aware society.

Keywords: performance; risk; loss; collapse; safety.

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, mainly 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 by defining 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 & 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):

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$$\lambda_f = \int_0^{+\infty} P[f|IM = im]|dH(im)| \tag{1}$$

This modernised approach quantifies the building performance in an overall risk sense. It is flexible in its definition of failure, allowing consistent consideration across all pertinent limit states (e.g., the 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 mainly been popular within academic research or specialised reports (CNR, 2014; FEMA, 2012) rather than widespread code implementation for practitioners to use. An additional problem has remained what values of collapse risk or economic loss can be considered acceptable limits when implementing such avant-garde approaches.

This paper reviews risk-targeted seismic design methods proposed in the literature along with current code-based approaches. They are generally described before comparing them based on design objectives, ease of implementation, and how PBEE-compatible they are in the modern context. Then, the paper discusses how these methods may be considered in future approaches to building performance evaluation, integrating novel elements of collapse risk and economic loss limitation. In particular, discussions on the possible synergies in engineering and the insurance and risk industries are described and how they may benefit from further dialogue and collaboration towards a more resilient society. It is worth noting that related discussion has been presented by Freddi *et al.* (2021) regarding the technologies and approaches that have been and are under development to work towards increased resilience in general.

SEISMIC DESIGN OF STRUCTURES

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 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 as input, which is determined from a series of risk-targeted hazard maps developed for a target collapse risk of 1% in 50 years.

These methods can be reasonable approximations for the initial seismic design of structures. However, the actual performance of systems 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 et al., 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 significant variations observed between different structural typologies and configurations.

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 et al., 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 (i.e., Eq. (1)).

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 methods. Luco *et al.* (2007) introduced the concept of risk-targeted spectra (RTS) 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 (RTSA) method to be integrated with the current procedures in EC8. Krawinkler *et al.* (2006) also introduced an early iterative approach termed conceptual performance-based design (CPBD), 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 studies above are not intended to be an exhaustive list of available methods but rather some important proposals to integrate modern PBEE in seismic design.

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 used to screen solutions initially before detailing the structural members. The IPBSD framework uses mean annual frequency of collapse (MAFC), λ_c, to ensure an acceptable level of collapse safety directly 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, but as discussed in later sections, the actual targets are yet to be formalised. The target MAFC, $\lambda_{c,target}$, is set and used to limit the actual λ_c described by:

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

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

$$\lambda_y = \int_0^{+\infty} E[y]|dH| \leq \lambda_{y,limit} \quad (3)$$

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.

DISCUSSION OF PERFORMANCE-BASED SEISMIC DESIGN METHODS

A critical discussion is provided with a brief overview of some of the currently available seismic design methods given previously. Table 1 shows several design methods, which are described as follows:

- IPBSD proposed by Shahnazaryan and O'Reilly (2021);
- Force-based design (FBD) present in many seismic design codes (ASCE 7-16, 2016; CEN, 2004; NTC, 2018; NZS 1170.5:2004, 2004);
- Direct displacement-based design (DDBD) outlined by Priestley *et al.* (2007b);
- RTBF described by Cornell (1996), amongst others;
- CPBD proposed by Krawinkler *et al.* (2006);
- RTS proposed by Luco *et al.* (2007);
- YFS proposed by Vamvatsikos and Aschheim (2016);
- RTSA, comprising both the direct (D) and indirect (I) approaches, by Žižmond and Dolšek (2019).

The rows of Table 1 list several categories common to each seismic design method. These are abbreviated and described as follows in the following subsections:

- PO - performance objective(s), which represent the primary quantity that each design method targets, limits or bases itself upon;
- H - seismic hazard definition, meaning how seismicity is characterised in the design process;
- NL - non-linearity, meaning how ductile structural behaviour is accounted for to determine a suitable set of reduced design forces adequately;
- DD - relative difficulty and directness, meaning how difficult (i.e. is the method feasible with just a spreadsheet or is extensive non-linear response history analysis (NLRHA) required?) and direct (i.e. are multiple iterations needed to obtain the final solution?) the process is;
- PBEE - whether or not the method is risk-consistent;
- FLX - the flexibility of the method, meaning how easy it is to tailor the design targets beyond what it has been developed for.

Table 1. Comparison of critical similarities and differences of available seismic design methods.

	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	$H(Sa(T_1))$	$H(Sa(T_1))$	$H(Sa(T_1))$
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

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 & Mosalam, 2013) and structures designed this way did not provide the consistent level of safety they were perceived to have (Iervolino et al., 2018). This led to developments on how these approaches may be improved but maintained the same intensity-based process familiar to practitioners. RTS, RTBF and RTSA-I are examples of such developments, where some *behind the scenes* adjustments are made to keep the familiar intensity-based approach via a uniform hazard spectrum (UHS) while maintaining 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). In contrast, a recent proposal by Vamvatsikos *et al.* (2020) for Europe used λ_c.

YFS provides a way to identify structures limiting 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. This is one of the few methods that has attempted to incorporate economic losses into its formulation directly. However, how 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 specific collapse risk and limit the expected economic losses across 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 pivotal point highlighted by 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). For this reason, O'Reilly and Calvi (2019) introduced the restriction of the initial period range and the subsequent identification of sufficient lateral strength and ductility.

Characterisation of seismic hazard

The subsequent broad comparison is how they define seismic hazard. Traditional methods like FBD and DDBD rely on using a UHS at specified T_R levels. These UHS are anchored to some level of ground shaking computed using probabilistic seismic hazard analysis (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. The main problem with using a UHS is that to make the resulting design solutions risk-consistent, they need to have some modifications in how they are utilised or 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 generally 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 YFS employs, RTSA-D, RTSA-I and IPBSD.

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. In contrast, 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 to identify 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 computed via an incremental dynamic analysis (IDA) analysis on an equivalent single degree of freedom (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 assumed values for force reduction and subsequent verification, YFS and the proposed IPBSD method both utilise the SPO2IDA tool (Vamvatsikos & 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 before designing the structure without any numerical analysis.

Ease of implementation

A generic ranking has been provided regarding each method's relative difficulty and directness based on the authors' subjective opinions. 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 considered easy 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 moderate as they do not require any dynamic analysis to implement. If the designer is confident in the SPO2IDA tool's ability to characterise the structure's dynamic behaviour, 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.

Method flexibility

Regarding 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 et al., 2013; Silva et al., 2016). All other methods are deemed flexible as they let designers choose and tailor their specific design targets, increasing their appeal.

PBEE compatibility

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

DISCUSSION AND FUTURE DIRECTIONS

From the previous sections regarding existing seismic design approaches in building codes and some more novel and avant-garde methods being proposed in the literature, it is clear that progress is being made. That is, to move away from a traditional engineering methodology centred around forces and displacements in individual structures at specified seismic intensities and consider a broader definition of seismic performance that incorporates aspects of resilience, finance and risk. In addition to building codes, there are also sectors whose main priority is estimating and reducing risks related to disasters such as earthquakes. In particular, the Sendai Framework for Disaster Risk Reduction published by the United Nations in 2015 (UNISDR, 2015) reiterated the need to focus on people's health and livelihoods, with an explicit focus on reducing risk and loss of life (Article 16). The priorities for achieving this highlight the need to understand, manage and mitigate this mortality risk and economic impact. It also encourages the revision of existing or development of new building codes to foster disaster-resistant structures and adopt a "build back better" approach to increase resilience. Naturally, this shift in thinking will require input and dialogue between sectors (e.g., engineering, (re)insurance and risk management) regarding what acceptable thresholds and targets could be in addition to what the quantities to focus efforts on should be.

One of the aspects mentioned in Table 1 was the possibility of integrating potential seismic losses within engineering practice. EAL use is relatively novel in earthquake engineering practice (Eq. (3)) but is noted to be commonplace in other sectors. In the Global Earthquake Model (GEM) Foundation (2018) model, the global seismic risk map characterises risk worldwide. It uses the EAL (or AAL) normalised by the construction cost of the region to allow a relative comparison between regions worldwide at a lower resolution than any building-specific project. This illustrates some common ground, whose potential for dialogue when applied to an engineering context was also noted in Crowley *et al.* (2012), for example.

While the CPBD approach discussed previously was seen to be extensive and possibly too cumbersome to implement, many of the tools needed to implement such concepts practically have been developed in recent years. In particular, Shahnazaryan *et al.* (2021) has shown how storey loss functions (SLFs) relating a structural demand parameter like peak floor acceleration to an economic loss for buildings can be easily derived via a Python-based toolbox and gives comparable accuracy to more rigorous component-based methods. Furthermore, the accumulation of direct financial losses among specific structural typologies (e.g., school buildings (Carofilis et al., 2020)) with comparable characteristics may also be expected to have SLFs with similar functional forms. This has been recently observed for non-ductile infilled frames (Nafeh & O'Reilly, 2022), where the notion of a normalised SLF for specific typologies can be seen in Figure 1. This implies that should a representative normalising value be known for the building typology (or taxonomy class), estimates of repair costs could be quickly obtained and integrated into engineering practice. The question remains: where to obtain such information to formulate these SLFs to begin with? The costing information is a quantity primarily related to reconstruction and repair. It could come from a more structured dialogue with the engineering industry and also with regards to how much insurers would typically pay out for certain damage scenarios, for example. The same applies to the expected quantities of damageable components commonly found in certain building typologies and seismic fragility characterised via numerical simulation or experimental testing. The data required to build such libraries and the taxonomy definitions and unit values adopted are all sources of required intersectoral collaboration and discussion.

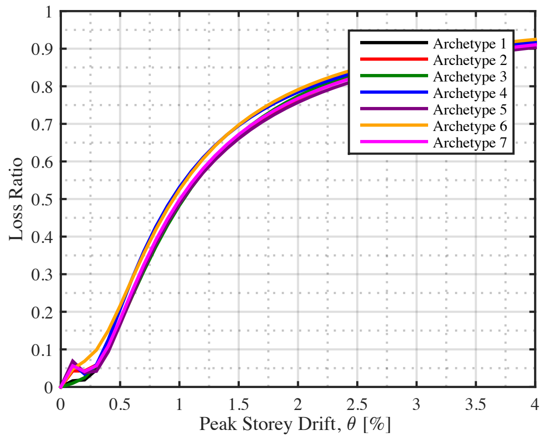

Figure 1. Comparison of the normalised storey loss functions for several infilled frame archetypes showing a relatively consistent trend among different buildings (Nafeh & O'Reilly, 2022)

The previous paragraph discussed the potential for standard or normalised loss curves for particular building types. This kind of development would have enormous value when considered within a seismic risk classification guideline similar to the Sismabonus system (Calvi et al., 2014; Cosenza et al., 2018) adopted in Italy. This type of system represents a powerful motivator for owners to capitalise on financial benefits offered by governments following evident risk class upgrades. The actual implementation of the current Sismabonus is not without its technical difficulties compared to a more rigorous analysis (e.g. O'Reilly et al., 2018). However, the underlying concept is still very much applicable. The ideas discussed here could be pursued to rectify these but again require appropriate collaboration.

Another issue is related to the acceptable fatality risk used when deciding on an acceptable MAFC for buildings (Eq. (2)). The link between these two quantities is dependent on several variables but could be formalised in a more structured approach, as discussed in Sinković & Dolšek (2020), for example. The Sendai Framework (UNISDR, 2015) also strives towards a direct reduction in fatalities due to natural hazards. This is underlined in Article 18(a), with the goal to substantially reduce global disaster mortality by 2030, aiming to lower the average per 100,000 global mortality rate. Similarly, the GEM Foundation discusses a Global Seismic Fatalities Map that depicts an estimate of average annual human losses due to earthquake-induced structural collapse of buildings. Information regarding expected risks and relative acceptance could be developed through the collaboration with engineering, industry and potentially social sciences to incorporate the perceptions and understanding of risk.

The discussion above has considered fatality risks, collapse and economic losses, in particular the direct financial loss associated with damage to a specific structure or component. What is also of enormous importance and ever-growing interest is the issue of indirect losses and how they may be utilised. Calvi et al. (2021) has discussed conceptual ways these could be potentially computed for practical decision-making purposes. Abarca *et al.* (2022), on the other hand, have outlined a simple approach to estimate the relative impacts of bridge structures in terms of indirect losses focusing on increased delays and travel times. This is not to mention the issue of downtime associated with repairs for ordinary buildings, which are yet to be fully integrated with engineering practice considerations. Interactions on the available information, tools and capabilities on this aspect would likely produce some innovative approaches.

SUMMARY

This paper has first presented a review of different design methods typically found in current design codes and guidelines and more contemporary methods available in the literature. It gave a detailed discussion into how they address different categories of desirability as an engineering approach. These were first related to the performance objectives used in design, seismic hazard characterisation and how the expected non-linear behaviour of the structures can be handled. It then looked at each method's difficulty to implement and overall directness by its flexibility in terms of how it can be modified to address different 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.

In light of this critical review, some discussion on the possible future directions involving collaboration between engineering, financial and risk management sectors was described. This was regarding economic loss consideration, fatality risks, indirect losses, and downtimes. Some of the recent advances on the engineering front were described, and potential starting points for further integration across sectors was suggested. It is hoped that this kind of discussion could foster further collaboration between sectors and strive towards the common goal of reduced and effectively managed risk.

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REFERENCES

Abarca, A., Monteiro, R., & O'Reilly, G. J. (2022). Simplified Indirect Loss Characterization for the Seismic Risk Assessment of Roadway Bridge Networks. *International Journal of Disaster Risk Reduction*.

ASCE 7-16. (2016). *Minimum Design Loads and Associated Criteria for Buildings and Other Structures*.

ATC. (2009). Quantification of building seismic performance factors. *Fema P695*, *June*, 421.

Calvi, G. M., O'Reilly, G. J., & Andreotti, G. (2021). Towards a practical loss-based design approach and procedure. *Earthquake Engineering & Structural Dynamics*, *50*(14), 3741–3753. https://doi.org/10.1002/eqe.3530

Calvi, G. M., Sullivan, T. J., & Welch, D. P. (2014). A Seismic Performance Classification Framework to Provide Increased Seismic Resilience. In A. Ansal (ed.) (Ed.), *Perspectives on European Earthquake Engineering and Seismology* (pp. 361–400). https://doi.org/10.1007/978-3-319-07118-3_11

Carofilis, W., Perrone, D., O'Reilly, G. J., Monteiro, R., & Filiatrault, A. (2020). Seismic retrofit of existing school buildings in Italy: Performance evaluation and loss estimation. *Engineering Structures*, *225*, 111243. https://doi.org/10.1016/j.engstruct.2020.111243

CEN. (2004). *Eurocode 8: Design of Structures for Earthquake Resistance - Part 1: General Rules, Seismic Actions and Rules for Buildings (EN 1998-1:2004)* (Comité Européen de Normalisation).

CEN. (2018). *Design of Structures for Earthquake Resistance (Draft) - Part 1: General Rules, Seismic Actions and Rules* *for Buildings (EN 1998-1:2018)*.

CNR. (2014). Istruzioni per la Valutazione Affidabilistica della Sicurezza Sismica di Edifici Esistenti. *CNR – Commissione Di Studio per La Predisposizione e l'analisi Di Norme Tecniche Relative Alle Costruzioni*.

Cornell, C. A. (1996). Calculating building seismic performance reliability: a basis for multi-level design norms. *11th World Conference on Earthquake Engineering*, 8. file://c/Documents and Settings/Jack/My Documents/1 Research/EndNote/References.Data/PDF/Cornell 11WCEE probabilistic basis-4222642179/Cornell 11WCEE probabilistic basis.pdf

Cornell, C. A., Jalayer, F., Hamburger, R. O., & Foutch, D. A. (2002). Management Agency Steel Moment Frame Guidelines. *Journal of Structural Engineering*, *128*(April 2002), 526–533. https://doi.org/10.1061/(ASCE)0733-9445(2002)128:4(526)

Cornell, C. A., & Krawinkler, H. (2000). Progress and Challenges in Seismic Performance Assessment. *PEER Center News*, *3*(2), 1–2.

Cosenza, E., Del Vecchio, C., Di Ludovico, M., Dolce, M., Moroni, C., Prota, A., & Renzi, E. (2018). The Italian guidelines for seismic risk classification of constructions: technical principles and validation. *Bulletin of Earthquake Engineering*, *16*(12), 5905–5935. https://doi.org/10.1007/s10518-018-0431-8

Crowley, H., Silva, V., Bal, I., & Pinho, R. (2012). Calibration of Seismic Design Codes using Loss Estimation. *15th World Conference on Earthquake Engineering*.

Douglas, J., Ulrich, T., & Negulescu, C. (2013). Risk-targeted seismic design maps for mainland France. *Natural Hazards*, *65*(3), 1999–2013. https://doi.org/10.1007/s11069-012-0460-6

Fajfar, P. (2018). Analysis in seismic provisions for buildings: past, present and future: The fifth Prof. Nicholas Ambraseys lecture. In *Bulletin of Earthquake Engineering* (Vol. 16, Issue 7). Springer Netherlands. https://doi.org/10.1007/s10518-017-0290-8

FEMA. (2009). NEHRP Recommended Seismic Provisions. *Fema P-750*, 406.

FEMA. (2012). *FEMA P-58-1: Seismic Performance Assessment of Buildings: Volume 1 - Methodology* (Vol. 1, Issue September).

Freddi, F., Galasso, C., Cremen, G., Dall'Asta, A., Di Sarno, L., Giaralis, A., Gutiérrez-Urzúa, F., Málaga-Chuquitaype, C., Mitoulis, S. A., Petrone, C., Sextos, A., Sousa, L., Tarbali, K., Tubaldi, E., Wardman, J., & Woo, G. (2021). Innovations in earthquake risk reduction for resilience: Recent advances and challenges. *International Journal of Disaster Risk Reduction*, *60*. https://doi.org/10.1016/j.ijdrr.2021.102267

Gkimprixis, A., Tubaldi, E., & Douglas, J. (2019). Comparison of methods to develop risk-targeted seismic design maps. *Bulletin of Earthquake Engineering*, *17*(7), 3727–3752. https://doi.org/10.1007/s10518-019-00629-w

Günay, S., & Mosalam, K. M. (2013). PEER Performance-Based Earthquake Engineering Methodology, Revisited. *Journal of Earthquake Engineering*, *17*(6), 829–858. https://doi.org/10.1080/13632469.2013.787377

Iervolino, I., Spillatura, A., & Bazzurro, P. (2018). Seismic Reliability of Code-Conforming Italian Buildings. *Journal of Earthquake Engineering*, *22*(sup2), 5–27. https://doi.org/10.1080/13632469.2018.1540372

Krawinkler, H., Zareian, F., Medina, R. A., & Ibarra, L. F. (2006). Decision support for conceptual performance-based design. *Earthquake Engineering & Structural Dynamics*, *35*(1), 115–133. https://doi.org/10.1002/eqe.536

Lazar Sinković, N., & Dolšek, M. (2020). Fatality risk and its application to the seismic performance assessment of a building. *Engineering Structures*, *205*, 110108. https://doi.org/10.1016/j.engstruct.2019.110108

Luco, N., Ellingwood, B. R., Hamburger, R. O., Hooper, J. D., Kimball, J. K., & Kircher, C. A. (2007). Risk-targeted versus current seismic design maps for the conterminous United States. *SEAOC 2007 Convention Proceedings.*

Nafeh, A. M. B., & O'Reilly, G. J. (2022). Unbiased seismic fragility estimation of non-ductile infilled RC buildings. *Soil Dynamics and Earthquake Engineering*.

NTC. (2018). *Norme Tecniche Per Le Costruzioni*.

NZS 1170.5:2004. (2004). *Structural design actions part 5: Earthquake actions*.

O'Reilly, G. J., & Calvi, G. M. (2019). Conceptual seismic design in performance-based earthquake engineering. *Earthquake Engineering & Structural Dynamics*, *48*(4), 389–411. https://doi.org/10.1002/eqe.3141

O'Reilly, G. J., & Calvi, G. M. (2020). Quantifying seismic risk in structures via simplified demand–intensity models. *Bulletin of Earthquake Engineering*, *18*(5), 2003–2022. https://doi.org/10.1007/s10518-019-00776-0

O'Reilly, G. J., Perrone, D., Fox, M., Monteiro, R., & Filiatrault, A. (2018). Seismic assessment and loss estimation of existing school buildings in Italy. *Engineering Structures*, *168*, 142–162. https://doi.org/10.1016/j.engstruct.2018.04.056

Priestley, M. J. N., Calvi, G. M., & Kowalsky, M. J. (2007). *Displacement Based Seismic Design of Structures*. IUSS Press.

SEAOC. (1995). *Vision 2000: Performance-based seismic engineering of buildings*.

Shahnazaryan, D., & O'Reilly, G. J. (2021). Integrating expected loss and collapse risk in performance-based seismic design of structures. *Bulletin of Earthquake Engineering*, *19*(2), 987–1025. https://doi.org/10.1007/s10518-020-01003-x

Shahnazaryan, D., O'Reilly, G. J., & Monteiro, R. (2021). Story loss functions for seismic design and assessment: Development of tools and application. *Earthquake Spectra*, *37*(4), 2813–2839. https://doi.org/10.1177/87552930211023523

Shahnazaryan, D., O'Reilly, G. J., & Monteiro, R. (2022). On the seismic loss estimation of integrated performance-based designed buildings. *Earthquake Engineering & Structural Dynamics*. https://doi.org/10.1002/eqe.3638

Silva, V., Crowley, H., & Bazzurro, P. (2016). Exploring risk-targeted hazard maps for Europe. *Earthquake Spectra*, *32*(2), 1165–1186. https://doi.org/10.1193/112514EQS198M

UNISDR. (2015). Sendai Framework for Disaster Risk Reduction 2015 - 2030. *Third World Conference on Disaster Risk Reduction, Sendai, Japan, 14-18 March 2015.*, *March*, 1–25. https://doi.org/A/CONF.224/CRP.1

Vamvatsikos, D., & Aschheim, M. A. (2016). Performance-based seismic design via yield frequency spectra. *Earthquake Engineering & Structural Dynamics*, *45*(11), 1759–1778. https://doi.org/10.1002/eqe.2727

Vamvatsikos, D., Bakalis, K., Kohrangi, M., Pyrza, S., Castiglioni, C. A., Kanyilmaz, A., Morelli, F., Stratan, A., D'Aniello, M., Calado, L., Proença, J. M., Degee, H., Hoffmeister, B., Pinkawa, M., Thanopoulos, P., & Vayas, I. (2020). A risk-consistent approach to determine EN1998 behaviour factors for lateral load resisting systems. *Soil Dynamics and Earthquake Engineering*, *131*(November 2019). https://doi.org/10.1016/j.soildyn.2019.106008

Vamvatsikos, D., & Cornell, C. A. (2005). Direct Estimation of Seismic Demand and Capacity of Multidegree-of-Freedom Systems through Incremental Dynamic Analysis of Single Degree of Freedom Approximation. *Journal of Structural Engineering*, *131*(4), 589–599. https://doi.org/10.1061/(asce)0733-9445(2005)131:4(589)

Vamvatsikos, D., Kazantzi, A. K., & Aschheim, M. A. (2016). Performance-Based Seismic Design: Avant-Garde and Code-Compatible Approaches. *ASCE-ASME Journal of Risk and Uncertainty in Engineering Systems, Part A: Civil Engineering*, *2*(2), C4015008. https://doi.org/10.1061/AJRUA6.0000853

Zareian, F., & Krawinkler, H. (2012). Conceptual performance-based seismic design using building-level and story-level decision support system. *Earthquake Engineering & Structural Dynamics*, *41*(11), 1439–1453. https://doi.org/10.1002/eqe.2218

Žižmond, J., & Dolšek, M. (2019). *Formulation of risk - targeted seismic action for the force - based seismic design of structures*. *January*, 1–23. https://doi.org/10.1002/eqe.3206