Performance-Based Seismic Design In Real Life: The Good, The Bad And The Ugly

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TRAILER
Designing a structure to deliver the desired performance under the uncertainties of hazard, materials and questionable models, is largely the Holy Grail of earthquake engineering. A number of methods have appeared in the literature claiming to offer this coveted prize, yet, in my very own opinion, they may require heavy computations or strict assumptions, sometimes offering a useful but partial solution, perhaps delivering something other than what the user expected, or even failing to deliver altogether. This does not necessarily detract from the usefulness of each method, but it does certainly mean that some differentiation among approaches should be maintained, despite all of them being bundled underneath the moniker of “performance-based”. Therefore, due to my heavy exposure to spaggeti westerns from a very young and tender age, my eternal fascination with the work of Sergio Leone and Ennio Morricone, and my desire to pay tribute to the shining geniuses that defined my childhood cosplay days, let me introduce to you what I consider to be *il buono, il brutto e il cattivo* of performance-based seismic design approaches. And like any good film, I am afraid you will have to read this paper to its conclusion to figure out which is which. I hope you enjoy it.

1 OPENING SCENE: REMINISCING UPON DEFINITIONS

There are many ways to define the performance of a structure, but very few that are unambiguous in terms of risk, and, in my way of thinking, ambiguity does not rhyme with performance. So, at least for the purposes of our discussion, we shall adopt a definition of a performance objective (or target) that respects risk. It is essentially a triplet of values: (a) a threshold or capacity value of response, damage or loss, C, (b) a maximum allowable mean annual frequency (MAF) of exceeding this threshold, λ_O, and (c) a desired confidence level of meeting this objective vis-à-vis epistemic uncertainty, x in [0.5,1). Thus, meeting an objective means that the x% percentile estimate (due to epistemic uncertainty) of the MAF of the demand, D, exceeding the capacity, C, should be lower than λ_O, or

$$\lambda_{x\%}(D > C) < \lambda_O \tag{1}$$

Optionally, one may choose to treat epistemic uncertainties by adopting a mean estimate of $\lambda(D>C)$, which is equivalent to prescribing a value of the confidence level x greater than 50% that depends on the dispersion of epistemic uncertainty, given a typical lognormal distribution assumption. Then, the triplet may be collapsed to a pair of MAF and threshold values.

$$\bar{\lambda}(D > C) < \lambda_O \tag{2}$$

where the bar signifies the mean.

The above definition is directly meant to close the loop between assessment and design by offering a performance target that is compatible with the state-of-the-art in how a structure is assessed within a performance-based probabilistic framework. In particular, it stems directly from the Cornell-Krawinkler framing equation adopted by the Pacific Earthquake Engineering Research (PEER) Center, (Cornell and Krawinkler 2000) for assessing structural performance:

$$\lambda(DV) = \iiint G(DV \mid DM) \left| \mathrm{d}G(DM \mid EDP) \right| \left| \mathrm{d}G(EDP \mid IM) \right| \left| \mathrm{d}\lambda(IM) \right| \tag{3}$$

DV is one or more decision variables, such as cost, time-to-repair or human casualties that are meant to enable decision-making by the stakeholders; *DM* represents the damage measures, typically discretized in a number of progressive damage states (DS) for structural or non-structural components and building contents; *EDP* contains the engineering demand parameters such as peak interstory drift, residual interstory drift and peak floor acceleration that can be derived from structural analysis; and, *IM* is the seismic intensity measure, for example represented by the 5%-damped first-mode spectral acceleration $S_a(T_1)$.

Equation 3 essentially provides a conceptual method for estimating the first term of Equation 1 and verifying whether a design complies with a stated objective. It can be employed to determine the MAF of exceeding a DV value or collapsed by reducing the order of integration to estimate the MAF of violating a DS level, or exceeding a value of the EDP. Similarly, a performance objective can be expressed in terms of a DV, a DS or an EDP, depending on how ambitious or demanding an owner may be. Thus, one may stipulate any of the following performance objectives:

- direct monetary losses exceeding C = 500,000€ with a maximum MAF of λ_O = 0.0021, or 10% in 50yrs, at a confidence of x = 75%;
- downtime exceeding C = 1 week with a maximum MAF of λ_O = 10% in 10yrs, at a confidence of x = 60%;
- no more than C = 20% of the columns enter, e.g., Damage State 3 with a maximum MAF of λ_O = 5% in 50yrs, at a confidence of x = 90%;
- maximum interstory drift less than 2% with a maximum MAF of λ_O = 10% in 50yrs, with a confidence of x = 75%.

Designing for performance means setting any number of such objectives according to the owner's requirements and offering a method that can produce a structural solution to satisfy them within the associated constraints imposed by architectural and operational considerations. The operative word in this statement is "to satisfy" the objectives, naturally via evaluating Equations 1 or 2. This is something that comes at a considerable cost, especially for objectives that may involve cost, casualties or downtime. It practically implies that one has to employ a model and analysis approach that can quantify and propagate uncertainty, incorporate the site hazard $\lambda(IM)$, and provide accurate enough estimates of EDP and, if needed, DM and DV to allow determining the MAF of violating relevant targets. Note also that meeting a number of performance objectives means being reasonably close to them, or, more accurately, being close to the most critical one that governs a given design. Massively overdesigning and claiming to achieve the performance target is not really the way to go. We want to be conservative vis-à-vis uncertainty, but only as much as the confidence level stipulates. Finally, the necessity of meeting different and non-standard objectives also implies that the engineer will probably not have the intuition to be able to size the structure according to these exacting requirements, thus preferably needing some method to guide the design process that is a bit more sophisticated than searching in the dark via trial and error.

2 THE BAD: NO PROBABILITY MEANS NO PERFORMANCE

A classic problem with the Bad guy is that he tends to masquerade as the Good one, at least in the start of the movie. Unfortunately, for Performance-Based Earthquake Engineering (PBEE) this confusion has persisted for a while in the profession, mainly due to the very influential ideas on performance stemming from the Vision 2000 (SEAOC 1995) document. This is an early PBEE approach (termed PBEE-1 by Gunay and Mosalam 2013) that helped drive the profession in the right direction but not to the end, as it does not include probability in a consistent manner, performing intensity-based (rather than risk-based) assessment. In terms of the classification of seismic design approaches by Vamvatsikos et al. (2016), this is a method that incorporates no uncertainty propagation, instead injecting any probability or safety at the input intensity and expecting it to "automatically" propagate to the output response, as determined in EDP, DM or DV terms. This description encompasses all current code-based design approaches, including guidelines utilizing "confidence/knowledge" factors applied at the loads and material properties to account for uncertainty. I am looking at you EN1998-3 (CEN 2005). As discussed in detail by Franchin et al. (2010), such factors applied at the input level of intensity and model parameters typically fail to convey the needed safety at the output level, in many cases becoming unconservative.

Displacement-based approaches (Moehle 1992) also fall in this category, having also had their share in increasing the apparent confusion. There are several flavors of displacement-based design (Sullivan et al. 2003), offering advantages in guiding the design process in an arguably more rational way that force-based approaches, at least for some types of structures; yet, they are not risk consistent. They may have appeared in the literature as performance-based (e.g., see the title employed by Priestley 2000) but by our current understanding of PBEE, they are not. There is no hazard curve and no uncertainty propagation, thus no proper probability implementation. It is important to state that this does not necessarily mean that they are bad design methods in general and that the research invested in them has gone to waste. They are simply not risk-consistent and they cannot guarantee meeting a performance objective. They are bad for performance.

Another, perhaps surprising candidate for the role of the Bad is the concept of risk-targeted spectra (Luco et al. 2007), used on their own as the means to deliver a guaranteed collapse performance. This is generally due to a misunderstanding of their role, as risk-targeted spectra were never meant to guarantee performance of any specific structure but only to strive for harmonized (i.e., uniform) collapse risk across different sites. This is not to say that uniform risk is not a worthwhile goal, but in reality you do not really know what that risk is. There is indeed a target risk used to calculate the spectra, but the assumption of a single collapse fragility function to characterize all types of structures (from unreinforced masonry huts and timber stables to steel skyscrapers) to be designed in a given site, is a bit too broad an assumption to impart any kind of reliability on the output performance.

Finally, let us turn our guns to the latest generation of risk-based *class-level* behavior or strength-reduction factors. This, for example encompasses the FEMA P695 (2009) guidelines and the recent INNOSEIS proposal for an EN1998-compatible approach developed by a consortium of European Universities (Vamvatsikos et al. 2017). Yes, apparently I am one of the perpetrators myself (but give me credit for an ugly comeback later on). Again, such behavior factors may be perfectly suited to harmonizing risk among different types of lateral-load-resisting systems for specific hardwired limit-states, yet they cannot accurately deliver the required performance. They can only increase our chances that a minimum safety is respected.

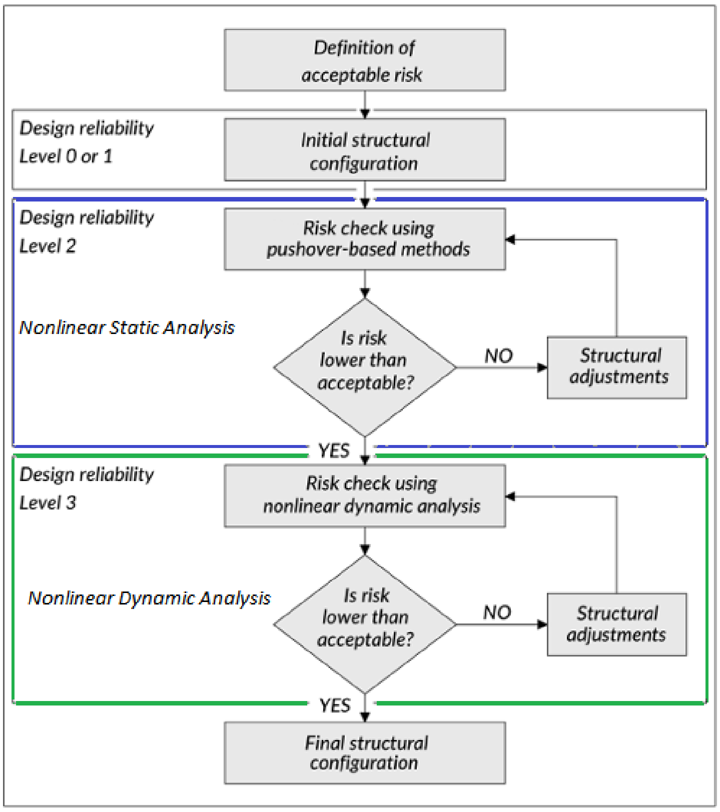

Figure 1. Flowchart of a possible realization of a performance-based design approach as proposed by Sinkovic et al. (2016) (adapted from http://www.smartengineering.si).

3 THE UGLY: WIN SOMETHING – LOSE SOMETHING

Our Ugly character has good intentions at heart, but either delivers at too high a price, or fails to deliver in full. The first case concerns methodologies that are based on design and analysis iterations using nonlinear analysis (static or preferably dynamic) to assess performance according to Equation 3. Several such risk-consistent approaches have appeared in the literature (e.g., Wen 2001, Krawinkler et al. 2006, Zareian and Krawinkler 2012). Their problem usually lies in not offering any a strategy to converge to a solution without unguided trial-and-error iterations. Essentially, such approaches are a PBEE assessment method within an loop of user-selected structural adjustments, whereby the assessment is performed by a static pushover approach or a nonlinear dynamic approach, or both (Figure 1). That is not to say that such a method does not work, but the pain of design-analysis cycles when doing PBEE assessment is such that one had better minimize their number lest the process becomes a computational beast of terror. In general, such frameworks work well conceptually, but they need considerable experience and intuition for practical application. Unfortunately, designing for performance is when most engineers become beginners again, as non-standard performance objectives often mean non-standard solutions, typically throwing past experience out of the window. Recognizing this issue, for example, Sinkovic et al. (2016) have offered conceptual rules for helping engineers in improving reinforced concrete frames to achieve a higher performance. Still, such rules only offer qualitative not quantitative guidance, thus not mitigating the issue.

One method to relieve the human user from the burden of choosing the next design in a trial-and-error scheme is to replace him or her by a computer. This means leaving the selection of candidate designs to (some fancily-named bio-inspired flavour of) a genetic algorithm optimization scheme that can reach at least a locally optimal design according to one or more performance objectives. Several such examples exist in the literature: Vamvatsikos and Papadimitriou 2005, Foley et al. 2007, Mackie and Stojadinovic 2007, Fragiadakis and Papadrakakis 2008, Fragiadakis and Lagaros 2011, Rojas et al. 2011. Here, the price to pay is in the need to create the appropriate software implementation, and in the requirement for large-scale computations, as genetic algorithms are like having a myopic shooter trying to hit an elusive target with a shotgun. The result is a lot of attempts (i.e., design candidates) and a heavy computational expense, unless one decides to compromise on the accuracy by limiting the number of records/analyses or foregoing dynamic analysis for pushover. Such an approach may still succeed, but at present it is only applicable at the academic level. One can foresee engineering software that can implement it in practice but only if tied to some fairly powerful computer system to crunch the numbers, the likes of which is not yet available to engineering offices. The rise of cloud computing and outsourcing of computational power to the servers of Google, Microsoft and Amazon might yet save the day.

Finally, it seems that two Bad guys put together may actually make for a reasonable Ugly one. Risk targeted spectra combined with risk-consistent class-level behaviour q-factors are such a possibility. The double harmonization achieved by the two complementary approaches can function reasonably well, but only for specific sets of performance objectives hardwired into the selection of the behavior q-factors, and partly in the generation of the risk-targeted spectra. Still, the conservatism implied in this approach simply means that we fail in achieving reasonable accuracy, as mandated earlier. It is probably fine for the masses, but bad for the individual building, as the conservatism may be too high, or, in some cases, not enough. The generous uncertainties employed everywhere in such methods tend to increase the conservatism quite a bit, but this may not be enough for buildings that deviate significantly from the norm, i.e., from the archetypes used to derive the q-factors. Still, this ugly and messy approach is fully compatible with current codes and becomes an easy-to-apply step in the right direction.

This is the case of the risk-targeted spectra combined with strength reduction factors derived via FEMA P695 (FEMA 2009). The latter may not be perfect, as it is not really using a MAF basis and multiple sites to verify the reduction factor. Instead, FEMA P695 employs intensity-based verification to assure a mandated maximum probability of collapse, regardless of site and hazard. Still, given that the risk-targeted spectra used in tandem are based on assuming a compatible collapse fragility function, at least there is enough consistency to claim that the collapse MAF is, with some non-trivial (but unknown) confidence, lower than the maximum allowable hardwired into the spectra assessment approach. Further improvements are obviously possible, e.g., by incorporating more performance objectives in the q-factor verification and even adopting a better MAF basis for verifying q-factors at multiple sites (Vamvatsikos et al. 2017). Still, even then, the objectives, the confidence etc. are hardwired into the code and the conservatism will tend to remain a bit too high. Still, there is no denying the ease of use of such methods. In some way, it is PBEE for the masses without any cost to the professional engineer whatsoever.

4 THE GOOD: ALWAYS DELIVERS

Our Good options are essentially Ugly ones with a small functional change to make them work better, perhaps giving credence to the notion that with a bit of makeup anybody can look good in a movie. The improvement is essentially the introduction of a scheme to quantitatively guide the selection of the next design. This is the polar opposite to the shotgun approach of genetic algorithms and the plan is to reduce excessive computations rather than relish in them. For this to work, obviously some approximations need to be made to reduce the computational load of running nonlinear analyses on an MDOF structures. We can distinguish two main ideas here: One is using an equivalent *linear MDOF* and the other is using an equivalent *nonlinear SDOF* as a proxy.

The first option is best exemplified by the work of Franchin and Pinto (2012), and more recently Franchin et al. (2018). It is based on employing an equivalent linear MDOF system for analysis in each iteration and using a steepest descent optimization approach to guide the redesign process at each step. Actually in its latest version this is a 16 step complex process that is meant for software application, yet it arguably remains a more tractable (and probably faster) approach than genetic-style algorithms. Still, as only simple regular structures have been tried so far, it makes sense that the engineer would have to hand-tune parts of the design to achieve better performance. This is certainly not a deal breaker as it is a process that engineers are used to, leading us to pronounce such an approach as one of the Good guys.

On the other side of the spectrum, the use of a nonlinear SDOF proxy has been proposed, together with an assumption on the invariance of period or yield displacement to better guide the design process. The invariance of period basically underlines most of the recent proposals on deriving building-specific probabilistic or risk-targeted behavior factors. These essentially offer a building-specific approach to assessing performance and guiding the next iteration via an equivalent elastic design behavior factor based on site hazard and the desired performance objectives. Although not originally cast in this form, but more as a way to improve upon standard behavior factors by including the seismic hazard curve and propagating uncertainty to the output, such works include Chryssanthopoulos et al. (2000), Costa et al. (2010) and Zizmond and Dolsek (2017). They were not necessarily meant for iterations, but perhaps a single step only application. Still, it is not such a grand leap of imagination to include them within an iterative approach that can surely let them get closer to a PBEE design ideal, better being able to match the required performance objectives after a few cycles.

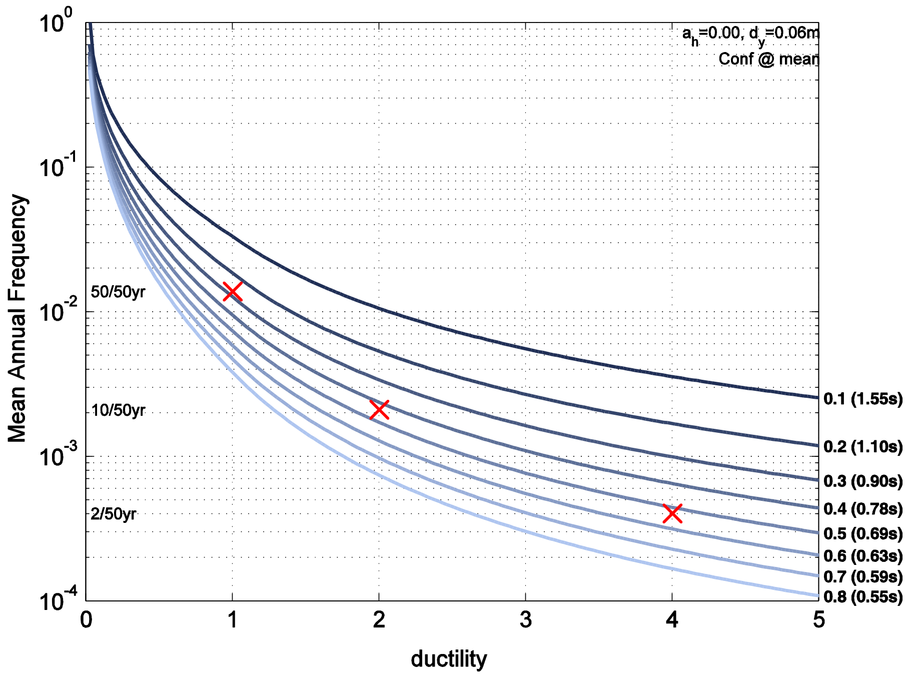

Figure 2. Yield Frequency Spectra showing contours for base shear ratios of 0.1 – 0.8 determined for an elastoplastic system at a high-seismicity site. “X” symbols represent discrete performance objectives at ductilities of 1, 2, and 4 at 50%, 10% and 2% in 50yrs exceedance rates, respectively. The largest of the base shear ratios required by each performance objective governs the design; here this is 0.53 with a required period of 0.68s for this rather aggressive California site. [adapted from Vamvatsikos and Aschheim 2016].

Arguably, and in no small part since I am a co-author of several relevant papers, an even better approach for many structures is the assumption of a constant yield displacement, rather than period, to guide design (Aschheim 2002). This concept has been incorporated in the yield frequency spectra approach of Vamvatsikos and Aschheim (2016). Herein, one needs to select a yield displacement, something that tends to be far easier for many (if not most) structures as it depends on configuration and not strength. Then, suggest a capacity curve shape (e.g., elastoplastic) and convert all EDP/DM/DV thresholds associated with performance objectives into global ductility values. The intersection of yield frequency spectra and ductility-MAF points (Figure 2) provides the required strength and stiffness to achieve the performance objectives. Obviously, as in all cases involving equivalent SDOF systems, the more complex, higher mode influenced and asymmetric the structure is, the more you will need to iterate. For simpler, regular buildings, though, convergence is typically achieved within a single step (Katsanos and Vamvatsikos 2017).

5 THE FINAL DUEL: THE GOOD DOES NOT ALWAYS WIN IN REAL LIFE

Bad methods are currently dominating design. In their defence, they were never meant to be performance-based, but this is an excuse that is getting too old. Unfortunately, probability often seems to be a touchy issue with the seismic code. It is tough to include it properly, without overcomplicating the code, while also convincing engineers that it is not the devil incarnate. Practicing engineers seem to be addicted to simple expressions and deterministic concepts, perhaps unsurprisingly so, since their job is quite complicated already. In other words, the Bad of our movie may very well keep wining for a decade or two.

Ugly methods based on genetic optimization may offer some simplicity in application, assuming of course the right software comes along, at the obvious expense of computations. It may not be too hard to imagine a highly efficient optimization guided by some version of artificial intelligence software as computers and software gets faster and better. After all, neural networks have already been proposed as a generic approach to provide fast estimation of nonlinear response (e.g., Papadrakakis and Lagaros, 2002). On the other hand, risk-targeted spectra and risk-consistent q-factors will probably provide the bulk of the improvement for the profession, catering to the vast percentage of the newly-designed structures for which accurate performance assessment simply does not make sense in terms of economics and time spent.

The Good methods presented may actually come to be useful for the select buildings that truly need them, at least in the meantime until even better approaches come along, or faster computers make the computational burden of genetic-style shotgun search go away.

So, who wins the final duel? If you ask me, like any good cinephil, I will always root for the Good guy. In this era of political correctness I will not even mind if the Ugly guy stays around and dominates the scene for a while. But I will certainly not tolerate the Bad being the last guy standing. Not in the name of performance.

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