Performance-Based Design with Application to Seismic Hazard

By Margaret Tang, Eduardo Castro, Flavio Pedroni, Andrzej Brzozowski, and Mohammed Ettouney

The development and use of performance-based design (PBD) of buildings has been in progress for several years, primarily within the seismic and blast communities. Within the engineering community as a whole, the use of PBD is being considered for applications to specific design issues such as progressive collapse, as well as full-scale infrastructure projects such as bridge designs.

Seismic PBD was introduced in FEMA 273/274, published in October 1997, which was then reissued in November 2000 as FEMA 356 – *Prestandard and Commentary for the Seismic Rehabilitation of Buildings*. It is generally accepted that these efforts constituted the first generation of seismic PBD. ASCE 41-06 – *Seismic Rehabilitation of Existing Buildings* has since superseded both versions of the FEMA standard.

Since 2002, there has been an ongoing effort by FEMA to generate a second generation of seismic PBD. This updated version incorporates details of analytical and design techniques, and quantifies performance measures and uncertainties. This is compared to the discrete qualitative measures offered by the first generation. Additionally, the second generation utilizes component and system fragilities, which relate structural performance metrics to the probability of occurrence or exceedance.

One of the main advances that the second generation seismic PBD paradigm offers is that it acknowledges the uncertainty present in seismic design of buildings, or any other infrastructure. The uncertainties in defining the seismic hazard, performing the design process, and estimating consequences are all included within the PBD paradigm. This is in sharp contrast with prescriptive designs. Admittedly, uncertainties are also accommodated to a certain extent in prescriptive designs: Allowable Stress Design (ASD) utilizes factors of safety and Load and Resistance Factor Design (LRFD) accounts for load factors and strength reduction factors, as the name implies. Yet PBD allows for far more freedom in prescribing desired degrees of exceedance levels and probabilistic levels for the building and events on hand. For example, a particular building stakeholder might decide that a non-exceedance probability of 95% is needed for the performance of the building during a seismic event. A stakeholder for a different building might decide that an 85% non-exceedance probability is more appropriate. The ability to determine an appropriate uncertainty level can be one of the major advantages of PBD.

Prescriptive vs. Performance Design Paradigms

A central difference between the traditional prescriptive design method and PBD is in the design objectives, as illustrated in *Figure 1*. While prescriptive designs require achieving an acceptable demand-to-capacity (D/C) ratio, the objective of PBD is to achieve a specified level of performance, as correlated to appropriate consequences, which may be measured in several ways including as monetary cost. Each of these methods requires design iterations until either an acceptable D/C ratio (for prescriptive design) or a desired performance level (for PBD) is achieved.

Another difference between the prescriptive design and PBD paradigms lies in their computational underpinnings. For prescriptive design, this relates to capacity and demand, and is based on structural reliability methods. PBD is based on risk methods that consider hazards, vulnerabilities and consequences. In this context, hazards and vulnerabilities are analogous to demand and capacity, respectively. However, PBD also accounts for the consequences associated with the hazards and vulnerabilities.

The third major difference between these two approaches lies in the steps that are taken in addressing the design considerations. For traditional prescriptive methods, the seismic hazard level and the acceptable level of damage in the structure is determined by prevailing building and design codes. In performance based design, both of these considerations are addressed during the design process, along with anticipated consequences and uncertainties in the design and analysis process. These decisions are made based on a desired level of performance, rather than a predetermined set of codes.

Design decisions in PBD are based largely on the building stakeholders, namely, the building owner. It is these stakeholders that will determine the initial cost investment in design and construction, and this will drive the level of performance and the associated consequences. PBD requires more effort in the early phases of design but it offers many advantages: 1) potential cost savings in the long run, 2) the option of continued operations and immediate occupancy after seismic events (which can be of importance for sensitive

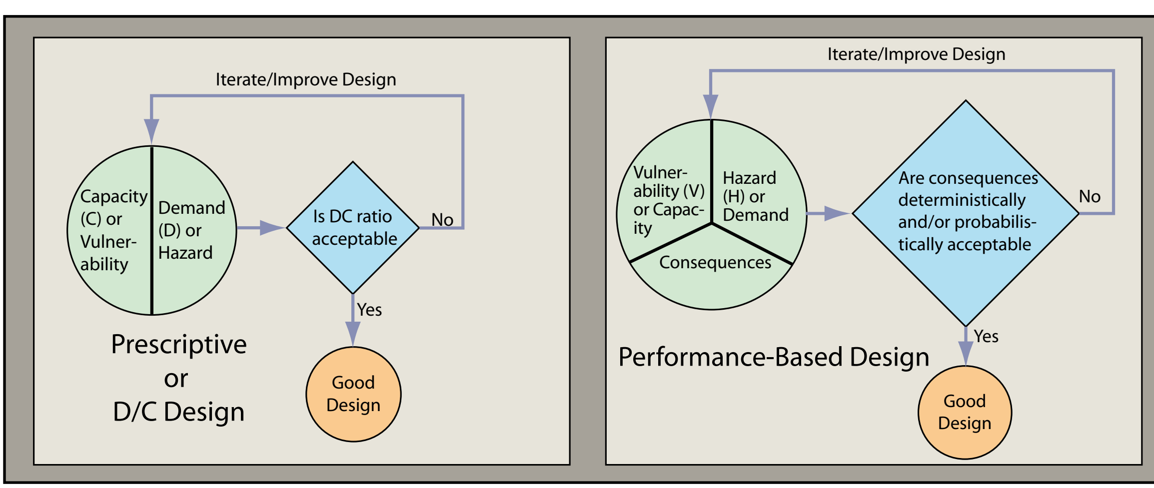


Figure 1: Prescriptive Design vs. Performance Based Design Paradigms.

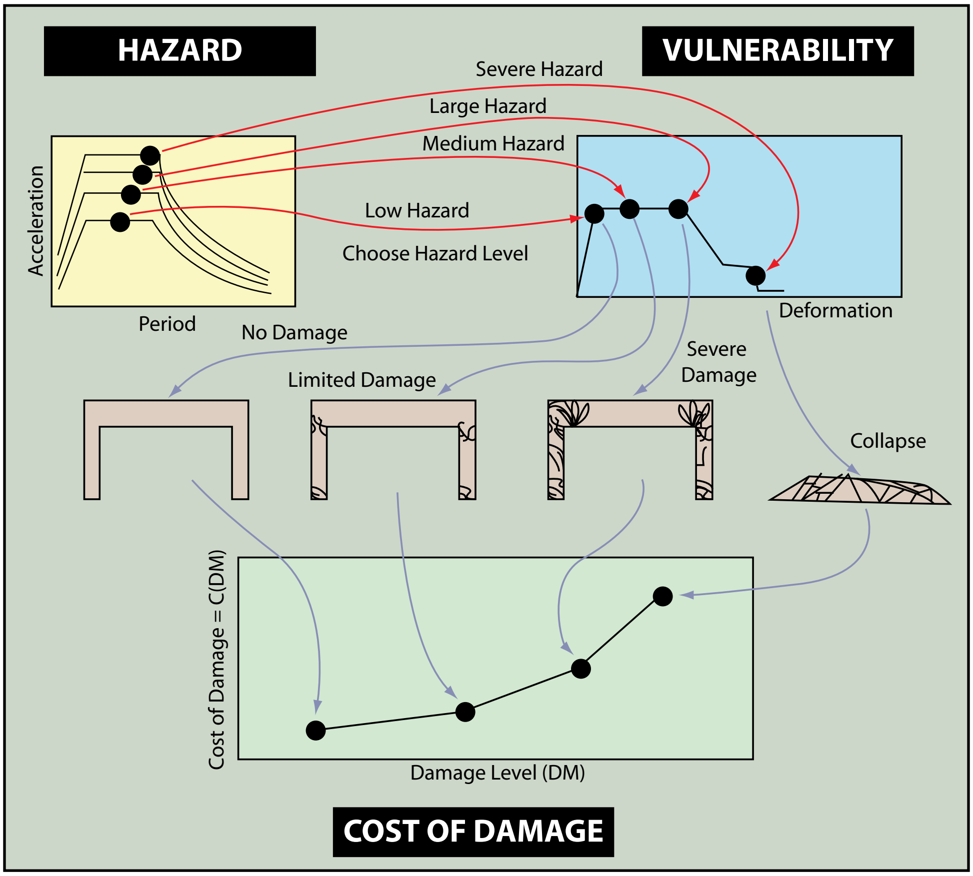


Figure 2: Performance Based Design Steps.

facilities), and 3) a clear quantitative picture on how the facility will perform during a seismic event, and what the consequences of such performance would be (i.e. no surprises to the stakeholders).

Elements of Performance Based Design

The three basic steps of PBD are the estimation of hazard, the evaluation of vulnerability, and the computation of consequences, shown schematically in *Figure 2*.

When using PBD, determining the design hazard level requires evaluation of the seismic event and the probability of occurrence. This can range in complexity from choosing only the hazard level and the shape of the design spectra to a more involved process, such as generating an ensemble of seismic acceleration time histories. In most situations, the designer needs to address issues such as return period (the duration of a seismic event at a given level) and maximum ground acceleration. In the second generation seismic PBD effort, the probability of the chosen seismic hazard is an integral part of the design input needs. This is necessary to compute the anticipated consequences of the design, as shown in *Figure 3*. Another feature of second generation seismic PBD is that it can be based either on a single scenario, such as a unique earthquake level, or on multiple earthquake levels with varied return periods. This latter approach is obviously more time consuming, since design calculations must be performed for each of the scenarios. However, the advantage of the multiple scenario approach is that it gives a more complete picture over the total life of the building. As noted earlier, prescriptive design methods do not address probabilities of occurrence or consequences, as these are implicitly addressed through the development of the design codes.

After the seismic input is defined, the building design process starts. The key differences between the two design approaches are in the acceptance criteria, the analysis techniques, and the analysis objectives. In traditional prescriptive design, the acceptance criteria is generally prescribed simply to ensure life safety, while PBD allows for varied acceptance criteria based on the determination of an acceptable level of earthquake damage to the structure.

In prescriptive design, evaluation of the building performance during a seismic event is usually performed using linear analysis, and the primary objective is to determine whether specific acceptance limits are met. In PBD, nonlinear analysis is preferred in order to

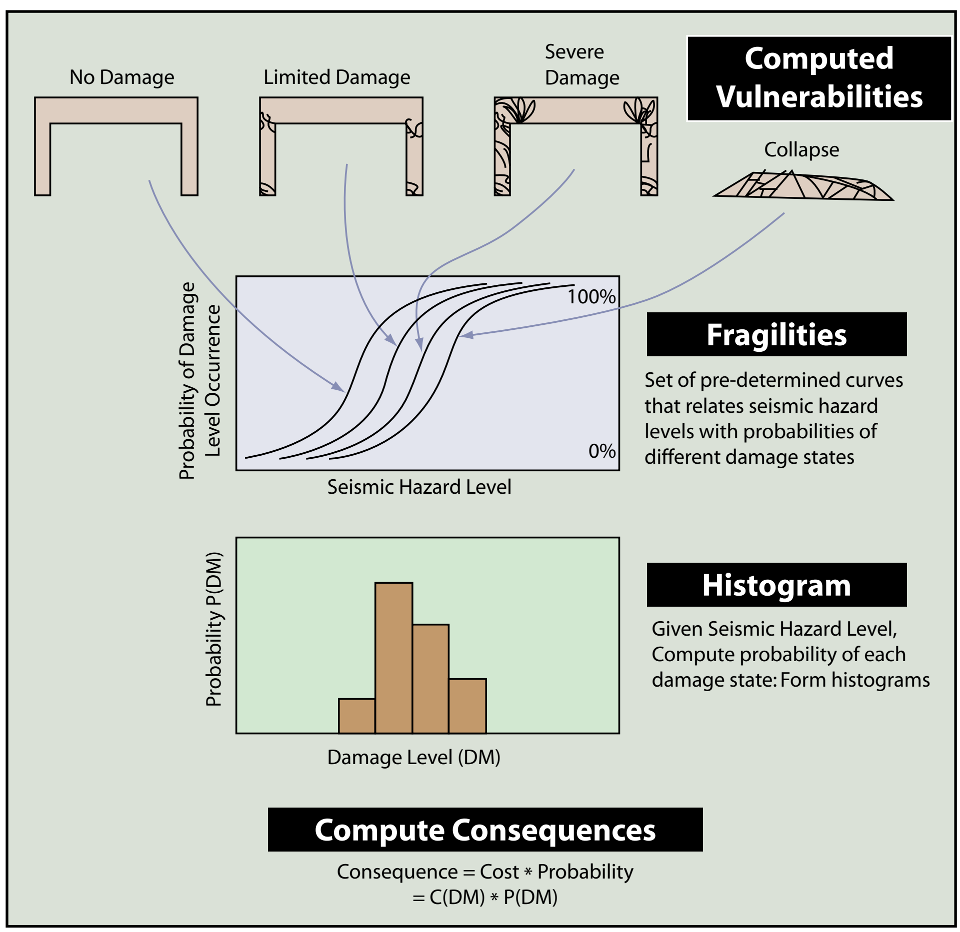


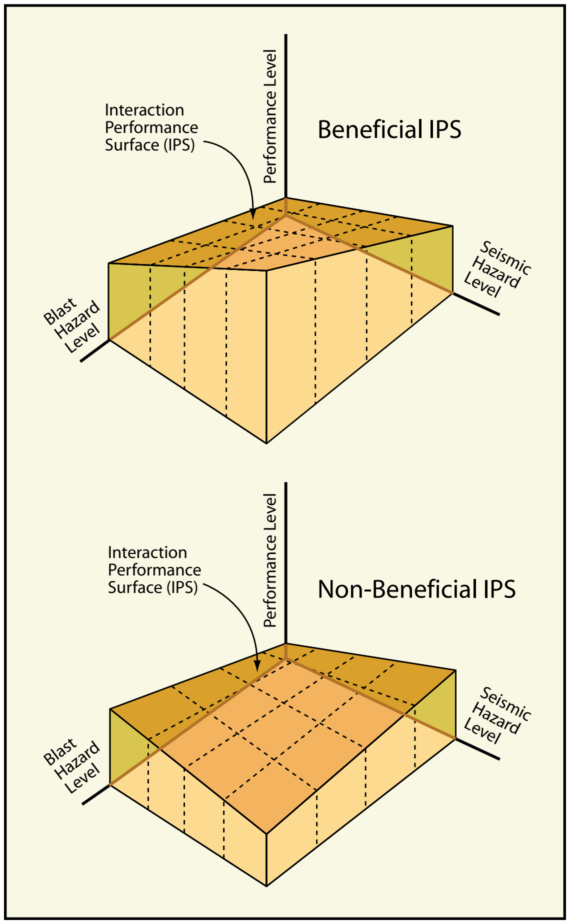
Figure 3: Computation of Risk.

compute damage types and levels, which will ultimately be used in determining the consequences of a particular design.

Computing types, levels, and probabilities of structural or non-structural damage due to an earthquake are not easy tasks. This is one area which is currently undergoing extensive research and development. An emerging technique for relating earthquake damage to uncertain inputs and computing the damage uncertainties is the use of fragility curves. *Figure 3 (page 21)* shows how fragilities are used in a PBD context. Component seismic fragilities have been under development for some time. Efficient, practical and general methods for system level fragility, on the other hand, are just starting to develop.

Considering consequences of seismic events in the design of buildings is perhaps the most important difference between prescriptive design and PBD. In the context of PBD, consequences generally relate to the building owner; the consequences to the neighborhood or other regional effects are beyond the scope of current PBD efforts. Consequences can be quantified in numerous ways; FEMA considers two types in particular: monetary and casualty. In order to compute the consequences, the probability of different types of damage (as estimated by fragility curves, for example) are combined with the predetermined relationship between damage level and associated costs. The estimated cost of the earthquake event can then be computed as shown in *Figure 3 (page 21)*. Computing cost based on uncertainties is one of the many definitions of risk, demonstrating that PBD is a risk-based paradigm.

After the consequences of the seismic event are computed based on the chosen performance levels, the building stakeholders (owner, architect, engineer, users, insurance companies, etc.) must decide if it is an acceptable cost (risk). If the costs proved to be too high, the performance levels are adjusted, and the whole procedure is repeated until an acceptable level of consequences is reached.



PBD and Multi-Hazard Design Considerations.

Future of Performance Based Design

PBD for earthquake engineering has been gaining interest for several years. Other fields of application include multi-hazard engineering, structural health monitoring, and life-cycle analysis.

Multi-hazard engineering is an ideal application of PBD as it requires the consideration of more than one hazard or extreme event at any given time, in an effort to increase safety and reduce subsequent costs. This can include seismic, wind, flood, bomb blasts, and progressive collapse. Prescriptive design methods are not applicable to this type of problem, as they tend to address scenarios with a single hazard or extreme event. Additionally, nonlinear analysis is recommended in order to accurately depict the performance of the structure in a multi-hazard scenario.

Structural health monitoring is emerging as an essential tool for preserving the health of infrastructures. Several sensors are placed on a structure in order to collect data on its performance over time. This data is useful in determining the response of a structure as a result of different stresses or hazards, which can ultimately be employed in PBD. Conversely, PBD techniques provide valuable information about damage in a structure due to a seismic event or other hazard. This can be useful in determining where to place the sensors in order to most effectively monitor any potential hotspots.

Life-cycle analysis, as the name implies, is the evaluation of performance over the life of a structure as a result of anticipated loads, stresses and hazards. It is closely tied to performance based design, as the latter is, at its most basic level, the relationship between a hazard and the anticipated response of the structure. The knowledge of life-cycle behavior is of immense importance to asset managers in their decision making efforts (e.g. inspection, prioritizing, budgeting, maintenance).

Performance based design offers numerous advantages as compared to traditional design methods. The challenges of implementing performance based design include smooth multidisciplinary integration and the added expertise of professionals. The advantages of PBD make meeting these challenges a worthwhile goal.▪

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