PEER Performance Based Earthquake Engineering Methodology, Revisited

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SUMMARY
A robust performance-based earthquake engineering (PBEE) methodology has been developed at the Pacific Earthquake Engineering Research (PEER) Center. The method is based on explicit determination of system performance measures meaningful to various stakeholder groups, such as monetary losses, downtime and casualties, in a rigorous probabilistic manner. Consequently, uncertainties in earthquake intensity, ground motion characteristics, structural response, physical damage, and economic and human losses are explicitly considered. PEER PBEE methodology has been explained and employed in various documents, most of which were useful academically without or with little attention to practical applications. However, there is an increasing trend towards the use of probabilistic performance-based design methods in recent years. This paper is an attempt to summarize the PEER PBEE methodology in a simplified manner to facilitate adoption by practicing engineers.

Keywords: PEER methodology, practicing engineer, probabilistic performance-based design, uncertainty.

1. INTRODUCTION

Traditional earthquake design philosophy is based on preventing structural and non-structural elements of buildings from any damage in low-intensity earthquakes, limiting the damage in these elements to repairable levels in medium-intensity earthquakes, and preventing the overall or partial collapse of buildings in high-intensity earthquakes. After 1994 Northridge and 1995 Kobe earthquakes, the structural engineering community realized that the amount of damage, the economic loss due to downtime, and repair cost of structures were unacceptably high, even though those structures complied with available seismic codes based on traditional design philosophy (Lee and Mosalam 2006). The concept of performance-based earthquake engineering (PBEE) has its roots from this realisation. Vision 2000 report (SEAOC 1995) is one of the early documents of the first generation PBEE in USA. In this report, performance-based earthquake design (PBED) is defined as a design framework which results in the desired system performances at various intensity levels of seismic hazard. The system performance levels are classified as fully operational, operational, life safety, and near collapse, while hazard levels are classified as frequent, occasional, rare, and very rare events. The designer and owner consult to select the desired combination of performance and hazard levels to use as design criteria (objective). The intended performance levels corresponding to different hazard levels are either determined based on the public resiliency requirements, e.g. hospital buildings, or by the private property owners, e.g. residential or commercial buildings. Subsequent documents of the first generation PBEE, e.g. FEMA-356 (2000), express the design objectives using a similar framework, with slightly different performance descriptions and hazard levels. The element deformation and force acceptability criteria corresponding to the performance are specified for different structural and non-structural elements for linear, nonlinear, static, and/or dynamic analyses. These criteria do not possess any probability distribution, i.e. element performance evaluation is deterministic. The defined relationships between engineering demands and component performance criteria are based somewhat inconsistently on relationships measured in laboratory tests, calculated by analytical models, or assumed on the basis of engineering judgment (Moehle 2003). In addition, element performance evaluation is not tied to a global system performance.

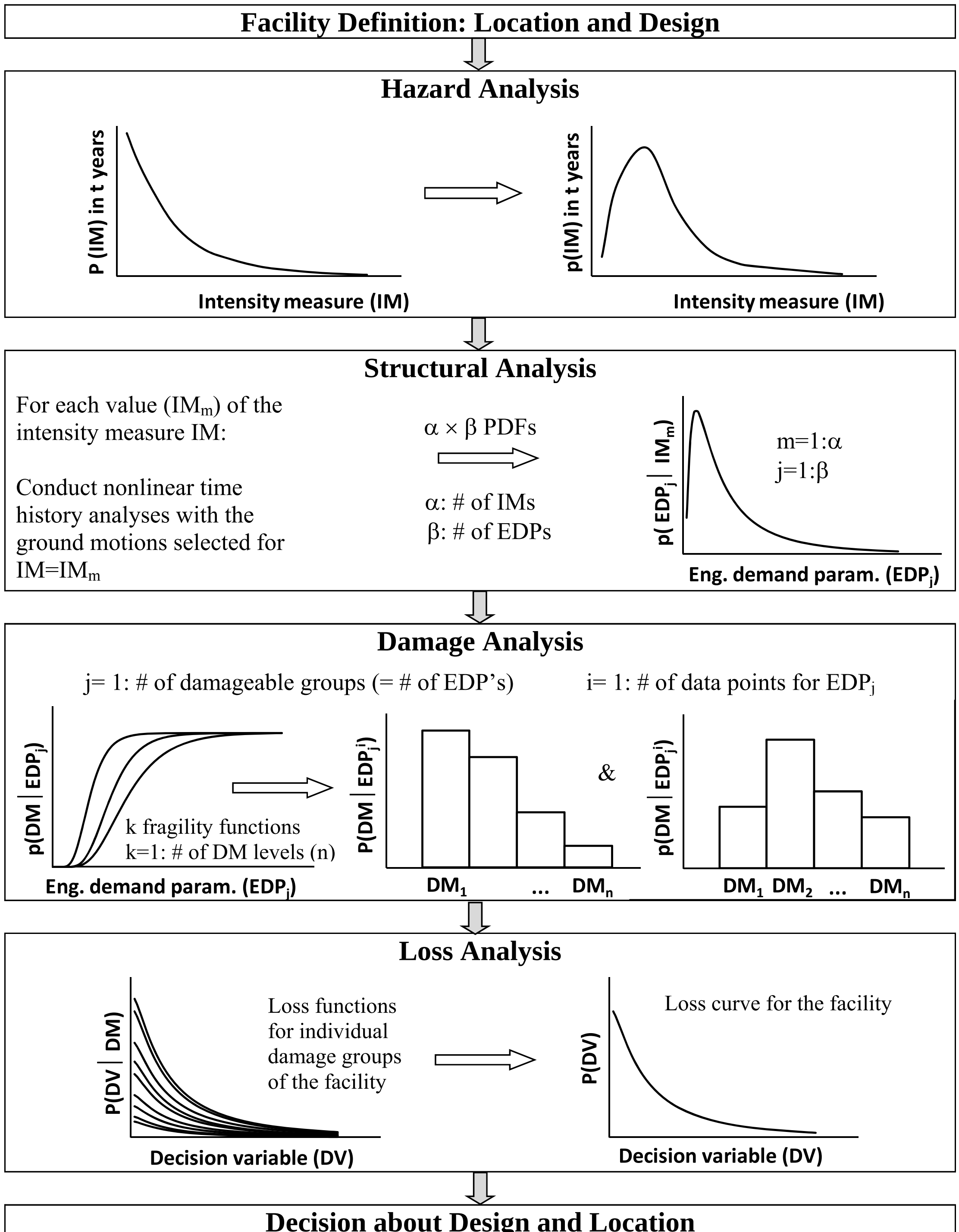
Considering the shortcomings of the first-generation procedures, a more robust PBEE methodology has been developed in the Pacific Earthquake Engineering Research (PEER) Center. One of the key features of PEER PBEE methodology is the explicit calculation of system performance measures, such as monetary losses, downtime (duration corresponding to loss of function), and casualties, which are expressed in terms of the direct interest of various stakeholders. Unlike earlier PBEE methodologies, element forces and deformations are not directly used for performance evaluation. A key feature of the methodology is the calculation of performance in a rigorous probabilistic manner without relying on expert opinion. Accordingly, uncertainties in earthquake intensity, ground motion characteristics, structural response, physical damage, and economic and human losses are explicitly considered in the method (Lee and Mosalam 2006). PEER performance assessment methodology has been summarized in various publications (Moehle 2003; Porter 2003; among others) and various benchmark studies have been conducted in (Comerio 2005; Krawinkler 2005; Mitrani-Reiser et al. 2006 among others).

Due to the probabilistic nature of the methodology and the various analysis stages it consists of, research on PEER PBEE methodology, examples of which are cited above, has been conducted mostly by the academics with little attention from practicing engineers. However, it is an accepted fact that the probabilistic PBED methods are gaining popularity and they are expected to be proposed for standard design codes in the near future. As an example, Rojas et al. (2011) developed algorithms which utilize the PEER framework for optimized and automated design of steel frame systems. The increasing trend to use probabilistic PBED as a design method is justified by the consequences of recent earthquakes, where they have shown that traditional earthquake design philosophy has fallen short of meeting the requirements of sustainability and resiliency. As an example, a traditionally designed hospital building was evacuated immediately after the 2009 L'Aquila, Italy earthquake, while ambulances were arriving with injured people. Similarly, some hospitals were evacuated due to non-structural and infill wall damages after the 2010 moment magnitude 8.8 Chile earthquake.

In this evolution process from traditional earthquake design philosophy to probabilistic PBED, this paper is an attempt to summarize and explain the PEER PBEE methodology in a simplified manner such that it can be appreciated and more easily adopted by practicing engineers. The summarized method is demonstrated and applied to an existing building on the UC-Berkeley campus.

2. PEER-PBEE FORMULATION

As schematically presented in Fig. 2.1, PEER PBEE methodology consists of four successive analyses: hazard analysis, structural analysis, damage analysis, and loss analysis. The methodology focuses on the probabilistic calculation of meaningful system performance measures to facility stakeholders by considering the above four analyses in an integrated manner where uncertainties are explicitly considered in all four analyses. Although each analysis is described separately in the following subsections, the uncertainties considered in each analysis can be summarized as follows: Hazard analysis considers the uncertainty of the components that define the earthquake hazard, such as fault locations, magnitude-recurrence rates and level of attenuation. Structural analysis accounts for the response of the structure to the earthquake hazard, considering the uncertainty from the structure such as material properties or damping, or from the characteristics of earthquake excitation, such as the differences in ground motion characteristics corresponding to the same hazard level. Damage analysis defines the level of damage corresponding to the response of the structure, considering the uncertainty in the pattern and history of the structural response. Loss analysis determines the amount of economic loss corresponding to damage considering the uncertainty in the distribution of damage throughout the structure, such as the variation of components resulting in the same damage level. In addition, uncertainty in economical values such as market prices is also taken into consideration. Due to the above uncertainties, the intensity of hazard, amount of structural response corresponding to hazard, level of damage corresponding to structural response, and amount of economic loss corresponding to the level of damage cannot be defined by a single value, instead by various values of different probabilities. PEER PBEE methodology combines these probabilities in a simple but consistent way using the total probability theorem, where the end result is the probability of exceedance (POE) of various values of a decision variable (DV) during the lifecycle of the building due to earthquake hazard. As mentioned previously, DV is typically a system performance measure in the direct interest of various stakeholders, such as monetary losses, downtime, or casualties.



P(X | Y): Probability of exceedance of X given Y, P(X): probability of exceedance of X, p(X): probability of X

Figure 2.1 Analysis stages of PEER PBEE methodology

2.1 Hazard Analysis

Hazard analysis is conducted to describe the earthquake hazard in a probabilistic manner, considering nearby faults, their magnitude-recurrence rates, fault mechanism, source-site distance, site conditions, etc., and employing attenuation relationships, such as ground motion prediction equations. The end result of hazard analysis is the hazard curve, which shows the variation of selected intensity measure (ground motion parameter) versus mean annual frequency (MAF) of exceedance (Bommer and Abrahamson 2006). Assuming the temporal occurrence of an earthquake is described by a Poisson model, POE of an intensity parameter in "t" years corresponding to a given MAF of exceedance is calculated with Eqn. 2.1 where "t" can be selected as the duration of life cycle of the facility.

$$P(IM) = 1 - e^{-\lambda(IM)\, t} \tag{2.1}$$

where IM is the intensity measure, λ(IM) is the annual frequency of exceedance of IM and P(IM) is the POE of IM in "t" years (Fig. 2.2). Probability of each value of IM ($p(IM_m)$) is calculated algorithmically using Eqn. 2.2 from the POE of IM.

$$\begin{aligned} &\text{for } m = 1 : \#\text{ of IM data points} \\ &p(IM_m) = P(IM_m) \quad \text{if } m = \#\text{ of IM data points} \\ &p(IM_m) = P(IM_m) - P(IM_{m+1}) \quad \text{otherwise} \end{aligned} \tag{2.2}$$

Peak ground acceleration, PGA, peak ground velocity, PGV, and spectral acceleration at the period of the first mode, $Sa(T_1)$, are examples of parameters that have been commonly used as intensity measures. These parameters are generally used as IM because most of available attenuation relationships, used in probabilistic seismic hazard analysis, are developed for these parameters.

Hazard analysis also includes the selection of a number of ground-motion time histories "compatible" with the hazard curve. For example, if $Sa(T_1)$ is utilized as IM, for each $Sa(T_1)$ value in the hazard curve, an adequate number of ground motions should be selected which possess that value of $Sa(T_1)$. Here, adequate number refers to the number of ground motions which would be adequate to provide meaningful statistical data in the structural analysis phase. In order to be consistent with the probabilistic seismic hazard analysis, selected ground motions should be compatible with the magnitude and distance combination which dominates the hazard for a particular value of IM (Sommerville and Porter 2005).

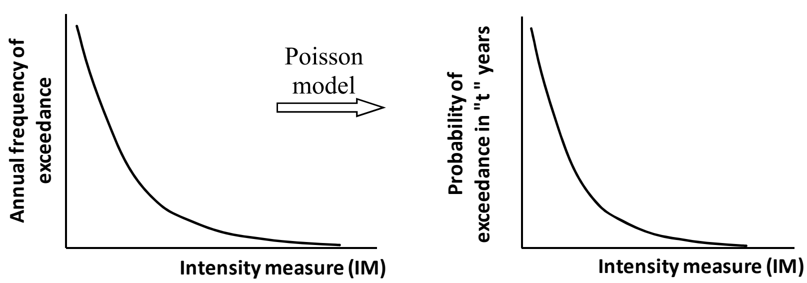


Figure 2.2 Correspondence between annual frequency and POE of IM

2.2 Structural Analysis

Structural analysis is conducted to determine the response of a structure to various levels and characteristics of earthquake hazard in a probabilistic manner. For this purpose, a computational model of the structure is developed. Uncertainties in parameters defining the structural model (e.g. mass, damping, stiffness, and strength) are considered by varying the relevant properties in the model. For each intensity level of earthquake hazard, nonlinear time history analyses are conducted to estimate the structural responses in terms of selected engineering demand parameters (EDP), using the ground motions selected for that intensity level. EDPs may include local parameters such as element forces or deformations, or global parameters such as floor acceleration and displacement, and interstory drift. For the structural components, element forces (such as the axial or shear forces in a non-ductile column) or deformations (such as plastic rotations for ductile flexural behavior) are more suitable, whereas global parameters such as floor acceleration are better suited for non-structural components, e.g. equipment. Interstory drift is a suitable parameter that can be used for the analyses focusing on both structural and non-structural components. The PEER-PBEE formulation requires a single value for EDP. Therefore, peak values of the above EDPs are generally employed.

It is possible to use different EDPs for different damageable components of a structure (denoted by EDP_j in Fig. 2.3). For example, interstory drift can be used for the structural system of a building (Krawinkler 2005), while using floor acceleration for office or laboratory equipment (Comerio 2005) of the same building. As a result of nonlinear time history analyses, the number of data points for each of the selected EDPs (i.e. EDP_j) at an intensity level is equal to the number of simulations conducted for that intensity level, i.e. the number of used ground motions multiplied by the number of variations in the structural model. For a structural engineer, the demanding part is the construction of different variations of a model, unless parameter-based software such as OpenSees (2010) is used. It is worth mentioning that Lee and Mosalam (2006) showed that ground motion variability is more significant than the uncertainty in structural parameters in affecting the local EDPs, based on analyses conducted for one of the testbeds of PEER PBEE methodology. In the same study, a method to determine the significance of the uncertainty in the various parameters of a model is described by conducting a "Tornado" analysis. Using a similar approach for an investigated facility, if the structural engineer arrives to a similar conclusion, the effort of introducing variations in the model can be spared.

It is likely to observe global collapse at higher intensity levels. Global collapse is treated separately in PEER PBEE methodology since its probability does not change from a damageable component to the other. In a simulation, global collapse corresponds to infinite increase of response for infinitesimal increases in input intensity, i.e. global dynamic instability. For a more realistic representation of global collapse, Talaat and Mosalam (2009) developed a progressive collapse algorithm based on element removal and implemented it into the structural and geotechnical simulation framework, OpenSees (2010), which is one of the main tools utilized for the application of PEER PBEE methodology. The probability of the global collapse event, $p(C|IM)$, can be approximately determined as the number of simulations leading to it divided by the number of simulations conducted for the considered intensity level. Probability of having no global collapse is defined as, $p(NC|IM) = 1.0 - p(C|IM)$. These probabilities are employed in the loss analysis stage as explained later.

A suitable probability distribution, e.g. lognormal, is used for each considered EDP (e.g. EDP_j) by calculating the parameters of this distribution from the data obtained from simulations with no global collapse (Fig. 2.3). The number of PDFs available as a result of structural analysis is $\alpha \times \beta$, where α indicates the number of IM data points and β indicates the number of considered EDPs.

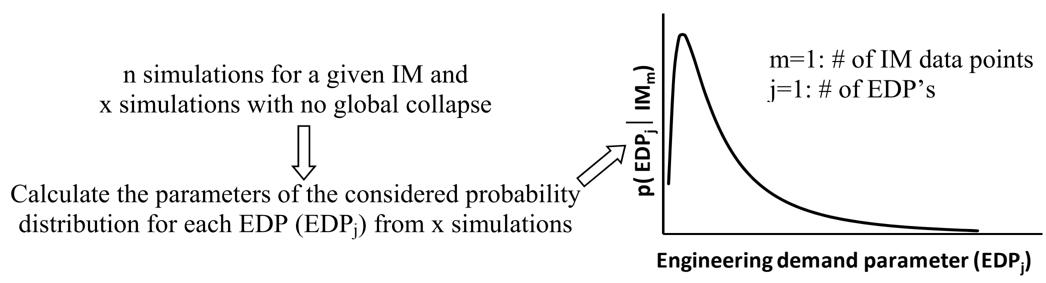


Figure 2.3 Determination of probability distribution functions (PDFs) of EDP from structural analysis

2.3 Damage Analysis

The improvement of PEER PBEE methodology compared to the first generation PBEE methods is the determination of DVs meaningful to stakeholders, e.g. monetary losses, downtime, casualties, rather than the determination of parameters meaningful to engineers only, e.g. forces or displacements. Therefore, after the determination of probabilities of EDPs in the structural analysis phase, these probabilities should be used to determine the POE or expected values of the DVs. This is achieved by the inclusion of the damage analysis and loss analysis stages as explained in the following.

The purpose of the damage analysis is to estimate physical damage at the component or system levels as a function of the structural response. While it is possible to use other definitions, damage measures (DMs) are typically defined in terms of damage levels corresponding to the repair measures that must be considered to restore the components of a facility to the original conditions (Porter 2003). For example, Mitrani-Reiser et al. (2006) defined DMs of structural elements as light, moderate, and severe (or collapse) corresponding to repair with epoxy injections, repair with jacketing, and element replacement, respectively. They defined DMs of non-structural drywall partitions as visible and significant corresponding to patching and replacement of the partition, respectively.

Damage level of a damageable component shows variance, even for the same value of EDP. This is mainly due to the differences in the pattern and history of the structural response. EDPs are generally represented as peak quantities. However, differences in the path of achieving the same peak value introduces differences in the observed damage and these differences set the variance of the DM corresponding to an EDP. Accordingly, a specific value of EDP corresponds to various DMs with different probabilities as shown in Fig. 2.4.

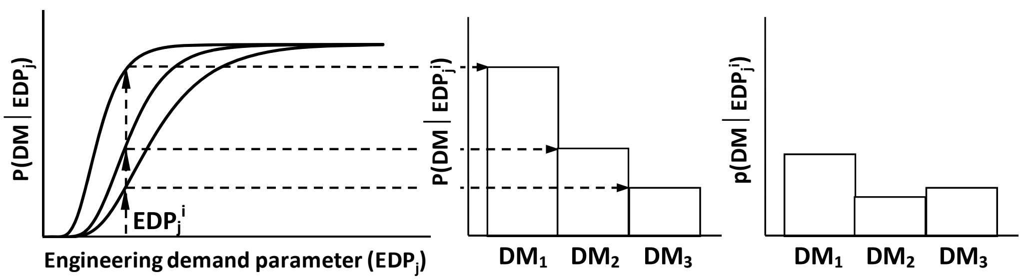


Figure 2.4 Probability of exceedance, P, and probability, p, of a damage level from fragility curves

The tool used to determine the above probabilities is the "fragility function," as commonly referred to in the literature. A fragility function represents the POE of a damage measure for different values of an EDP. Fragility functions of structural and non-structural components can be developed for a facility using experimental or analytical models. Alternatively, generic fragility functions corresponding to a general structure or component type can be used. The damageable parts of a facility are divided into groups (damageable groups) consisting of components that are affected by the same EDP in a similar way, i.e. the components in a group should have the same fragility functions. For example, Bohl (2009) used 16 different groups for a steel moment frame building including the structural system, exterior enclosure, drift-sensitive and acceleration-sensitive non-structural elements, and office content in each floor. For each damageable group (index j) and each EDP (index i) data point (EDP_j^i), the POE of a DM is available as a point on the related fragility curve (Fig. 2.4). Probability of a DM is calculated from the POE using the following algorithm:

$$\begin{aligned}&\text{for } k = 1:\#\text{ of DM levels}\\&p(DM_k | EDP_j^i) = P(DM_k | EDP_j^i) \quad \text{if } k = \#\text{ of DM levels}\\&p(DM_k | EDP_j^i) = P(DM_k | EDP_j^i) - P(DM_{k+1} | EDP_j^i) \quad \text{otherwise}\end{aligned} \tag{2.3}$$

2.4 Loss Analysis

Loss analysis is the last stage of PEER PBEE methodology, where damage information obtained from the damage analysis (Fig. 2.4) is converted to the final decision variables (DVs). These variables can be used directly by a structural engineer in the design process with the inclusion of stakeholders for decision-making about the design. Most commonly utilized DVs are stated as follows:

1. Fatalities: Number of deaths as a direct result of facility damage.
2. Economic loss: Monetary loss which is a result of the repair cost of the damaged components of a facility or the replacement of the facility.
3. Repair Duration: Duration of repairs during which the facility is not functioning.
4. Injuries: Number of injuries, as a direct result of facility damage.

First three of these DVs are commonly known as deaths, dollars and downtime (the 3 Ds).

In the loss analysis, the POE of the losses for different damageable groups at different DMs (loss functions) is determined. It is not practical to define every individual structural and non-structural component as a separate damageable group. Hence, the distribution of damage within the damageable group may result in different values of DVs for the same DM. If the DV is economic loss or repair cost, uncertainty that originates from the economical values, such as fluctuation in the market prices, is added to this uncertainty. Accordingly, a specific DM of a damageable group corresponds to various DMs with different probabilities represented by the loss functions in Fig. 2.5. As shown in this figure, the total number of loss functions present for a facility is $\gamma \times \lambda$, where γ and λ are the number of DMs and damageable groups, respectively.

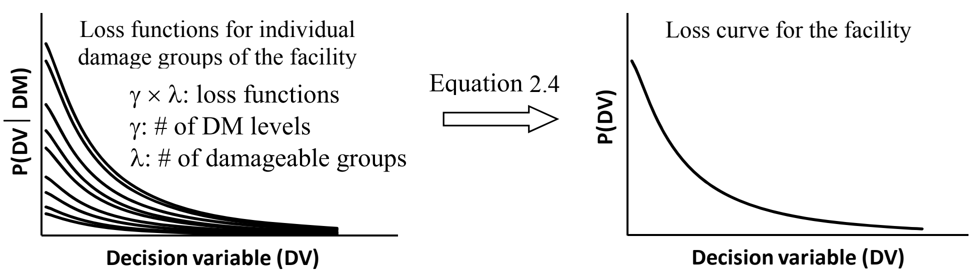


Figure 2.5 Loss functions for individual damageable groups

2.5 Determination of the Loss Curve

The end result of the PEER PBEE methodology is the loss curve, which describes the POE of the different values of a DV. The loss curve is obtained from the total probability theorem by combining the probability and POE values from the hazard, structural, damage, and loss analyses as follows:

$$P\left(DV_j^n \middle| EDP_j^i\right) = \sum_k P\left(DV_j^n \middle| DM_k\right) p\left(DM_k \middle| EDP_j^i\right) \tag{2.4a}$$

$$P\left(DV_j^n \middle| NC, IM_m\right) = \sum_i P\left(DV_j^n \middle| EDP_j^i\right) p\left(EDP_j^i \middle| IM_m\right) \tag{2.4b}$$

$$P\left(DV^n \middle| NC, IM_m\right) = \sum_j P\left(DV_j^n \middle| NC, IM_m\right) \tag{2.4c}$$

$$P\left(DV^n \middle| IM_m\right) = P\left(DV^n \middle| NC, IM_m\right) p\left(NC \middle| IM_m\right) + P\left(DV^n \middle| C\right) p\left(C \middle| IM_m\right) \tag{2.4d}$$

$$P\left(DV^n\right) = \sum_m P\left(DV^n \middle| IM_m\right) p\left(IM_m\right) \tag{2.4e}$$

where $P(DV_j^n|DM_k)$ is the POE of the n^{th} value of the DV for the j^{th} damageable group of the facility when DM k occurs (loss analysis outcome: loss function, Fig. 2.5), $p(DM_k|EDP_j^i)$ is the probability of the DM k when subjected to the i^{th} value of the EDP utilized for the fragility function of the j^{th} damageable group (damage analysis outcome: fragility function, Fig. 2.4), $p(EDP_j^i|IM_m)$ is the probability of the i^{th} value of the j^{th} EDP (EDP used in fragility function of the j^{th} damageable group) for the m^{th} value of IM (structural analysis outcome, Fig. 2.3), and $p(IM_m)$ is the probability of the m^{th} value of IM (hazard analysis outcome, Fig. 2.2). Moreover, $p(C|IM_m)$ and $p(NC|IM_m)$ are the probabilities of having and not having global collapse, respectively, under ground motion intensity IM_m. Finally, $P(DV^n|C)$ is the POE of the n^{th} value of DV in cases of global collapse. Krawinkler (2005) assumed a lognormal distribution for $P(DV^n|C)$ for the case of DV being the economic loss.

Calculation of the loss curve can be summarized with the following steps:

1. Determine the loss functions for each damageable group of the facility for each DM, $P(DV_j|DM_k)$.
2. Combine the loss and damage analyses results for each damageable group. Determine the POE of DV for each damageable group of the facility for each value of the EDP used in the fragility function of the group, $P(DV_j|EDP_j^i)$, Eqn. 2.4a, considering loss functions of step 1, $P(DV_j|DM_k)$, and probability of each DM from the relevant fragility function, $p(DM_k|EDP_j^i)$.
3. Combine the loss, damage, and structural analyses results for each damageable group. Determine the POE of DV for each damageable group of the facility for a given value of IM under the condition that global collapse does not occur, $P(DV_j|NC,IM_m)$, Eqn. 2.4b, considering the POE of step 2, $P(DV_j|EDP_j^i)$ and probability of each value of EDP used in the fragility function of the group when subjected to the ground motions compatible with the considered IM, $p(EDP_j^i\,|IM_m)$.
4. Combine the results of each damageable group. Determine the POE of DV for the facility for a given value of IM under the condition that global collapse does not occur, $P(DV|NC, IM_m)$ by summing up the POEs of DV for each damageable group, $P(DV_j|NC,IM_m)$, Eqn. 2.4c.
5. Combine the results of non-collapse and collapse cases. Determine the POE of DV for the facility for a given value of IM, $P(DV|IM_m)$, by summing up the POEs of DV for non-collapse and collapse cases weighted with the probabilities of these cases, Eqn. 2.4d.
6. Finally, include the hazard analysis results. Determine the POE of DV for the facility, P(DV), by summing up the POEs of DV for different IMs, $P(DV|IM_m)$, multiplied by the probabilities of these IMs, $p(IM_m)$, Eqn. 2.4e. P(DV) represents the POE in "t" years, the duration for which the POE values are calculated for the IM in hazard analysis.

Some simplifications, variations and comments related to Eqn. 2.4 can be stated as follows:

- The loss curve defined with Eqn. 2.4e considers all the possible scenarios for hazard, whereas in some applications of the PEER PBEE methodology, few IM (e.g. IM corresponding to 2, 10 and 20% of exceedance in 50 years) values are considered separately. In this case, Eqn. 2.4e is not used and the loss curves for individual IMs (different scenarios) are defined with Eqn. 2.4d.
- Expected value of DV can be calculated with Eqn. 2.4 by replacing the POE values in Eqn. 2.4 by the expected values (i.e. for example $E(DV_j^n|DM_k)$ instead of $P(DV_j^n|DM_k)$.
- It is observed that the loss, damage, and structural analyses results are summed in a straightforward manner in Eqn. 2.4a and 2.4b. However, integration of the hazard analysis to the formulation does not take place in such a way because of the presence of damageable groups and collapse and non-collapse cases and therefore requires Eqn. 2.4c to 2.4e. In order to have a direct demonstration of the total probability theorem, the POE of DV is presented in Eqn. 2.5 for the case of only non-collapse and single damageable group, where the equation is represented in the form of a triple summation.

$$P\left(DV^n\right)=\sum_m\sum_i\sum_k P\left(DV^n\middle|DM_k\right)p\left(DM_k\middle|EDP_j^i\right)p\left(EDP_j^i\middle|IM_m\right)p\left(IM_m\right) \tag{2.5}$$

3. DEMONSTRATION EXAMPLE

PEER PBEE methodology is applied in detail on the University of California Science (UCS) building located on the UC-Berkeley campus. The considered building is a modern reinforced concrete (RC) shear-wall building which provides high technology research laboratories for organismal biology. Besides the research laboratories, the building contains animal facilities, offices and related support spaces. There are six stories and a basement, and the building is rectangular in plan with overall dimensions of approximately 93.27 m (306 ft) in the longitudinal (north-south) direction and 32 m (105 ft) in the transverse (east-west) direction (Comerio 2005). A RC space frame carries the gravity loads of the building, and coupled shear-walls and perforated shear-walls support the lateral loads in the transverse and the longitudinal directions, respectively, as shown in Fig. 3.1.

The building is an example for which the non-structural components contribute to the PBEE methodology in addition to the structural components, due to the valuable building contents, i.e. the laboratory equipment and research activities. Detailed information about the contents inventory and their importance can be found in (Comerio 2005). Only brief presentation of the analyses results are given herein. As an example of an intermediate result, Fig. 3.2 presents the fragility curves for the structural components, where the maximum interstory drift (MIDR) is employed as EDP. The resulting loss curves are presented in Fig. 3.3 for the actual case and for a hypothetical case where collapse is prevented for all intensity levels. The significant reduction of economic losses for the collapse-prevented case shows the effect of the collapse prevention mandated by the seismic codes from an economical perspective.

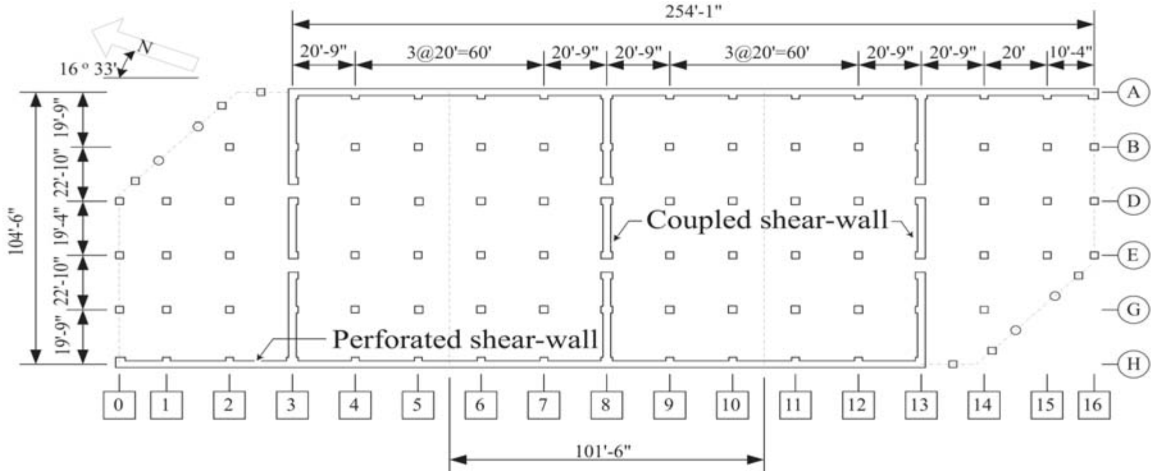


Figure 3.1 Plan view of the UCS building (Lee and Mosalam 2006)

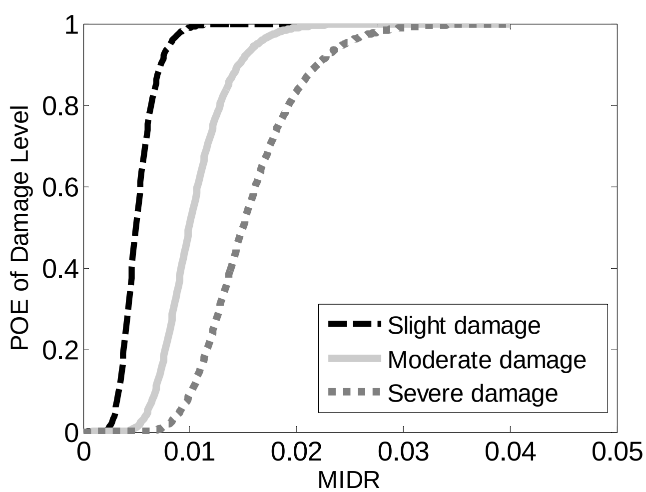


Figure 3.2 Fragility curves for structural components

4. CLOSURE

Amongst the various factors that determine the performance of a structure against earthquake hazard, a structural engineer has the main control on the structural design. PEER PBEE methodology provides a powerful tool to the structural engineer to evaluate the design at hand with the other influencing factors, such as the hazard or loss, which are known by the engineer in an uncontrollable manner. Hence, a designer can improve the design by considering all the influencing factors in an integrated manner, an example of which is shown in Fig 3.3 for the case of collapse prevention. In this regard, PEER PBEE methodology provides an effective design tool not only for the design of conventional structural types, such as moment resisting frames with unreinforced masonry infill walls, but also for the innovative and sustainable design and retrofit methods such as base isolation, rocking foundations, and self-centering systems. As shown in this paper, the method is based on the total probability theorem, which requires only an elementary knowledge of probabilistic concepts and therefore it can be easily adopted by the practicing engineers in this evolution process of the replacement of the traditional design methods by the probabilistic performance-based design methods.

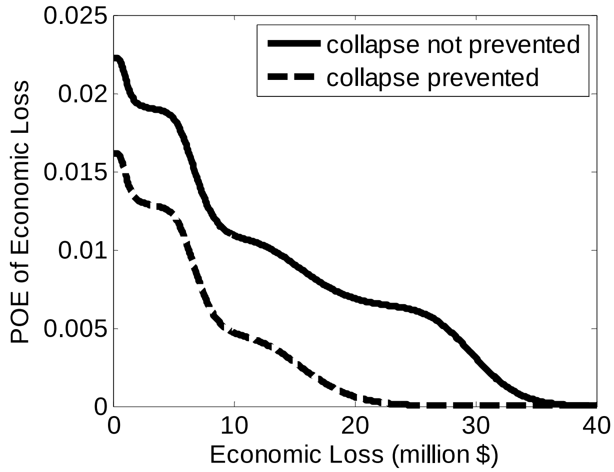


Figure 3.3 Improvement in the loss curve due to collapse prevention for UCS building.

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