

EVALUATION OF THE SEISMIC PERFORMANCE OF A CODE-CONFORMING REINFORCED-CONCRETE FRAME BUILDING - PART II: LOSS ESTIMATION

Judith Mitrani-Reiser¹, Curt Haselton², Christine Goulet³, Keith Porter⁴, James Beck⁵, and Gregory Deierlein⁶

ABSTRACT

Performance-based earthquake engineering (PBEE) is a methodology that incorporates desired performance levels into the design process. *Performance* in PBEE can be economic (e.g., expected annual losses), or expressed in terms of operability and safety performance (e.g., expected downtime due to safety tagging and/or repair). These performance objectives are relevant to various types of stakeholders and should be addressed in building loss estimation procedures. In this study, we consider the structural and economic performance of a code-conforming office building. An analytical approach for PBEE is implemented to evaluate the performance of this reinforced-concrete moment-frame building. The PBEE approach used is consistent with the Pacific Earthquake Engineering Research (PEER) center's framework, which is divided into four core analytical stages: hazard analysis, structural analysis, damage analysis, and loss analysis. Future losses of the building are uncertain because they depend on uncertain quantities, such as the shaking intensity of the earthquake, the mechanical properties of the facility, and the uncertain damageability and unit repair costs of the facility. An analytical approach is developed to propagate these uncertainties. This paper presents the mathematical foundation for the damage and loss analyses, and a description of its implementation into software. The results from running this software on multiple design variants of the building are presented, including seismic vulnerabilities as a function of shaking intensity and corresponding expected annual losses.

Introduction

The benchmark study presented here is a collaborative effort between Caltech, UCLA, and Stanford. The purpose of this study is to implement PEER's PBEE methodology and evaluate the economic performance of a new reinforced-concrete moment-frame office building.

¹Ph.D. Candidate in Applied Mechanics, Caltech, Pasadena, CA 91125

²Ph.D. Candidate in Civil and Environmental Engineering, Stanford University, Stanford, CA 94305

³Ph.D. Candidate in Civil and Environmental Engineering, UCLA, Los Angeles, CA 90095

⁴George W. Housner Senior Researcher in Civil Engineering, Caltech, Pasadena, CA 91125

⁵Professor of Engineering and Applied Science, Caltech, Pasadena, CA 91125

⁶Professor, Department of Civil and Environmental Engineering, Stanford University, Stanford, CA 94305

PEER PBEE Methodology Overview

Among other things, the PBEE methodology can be used to estimate the mean annual frequency with which a particular performance metric will exceed various levels for a given location (Porter 2003). The four main steps are presented in Fig. 1: hazard analysis, structural analysis, damage analysis, and loss analysis. The methodology is expressed mathematically in Eq. (1). In both the figure and the equation, $p[X|Y]$ denotes the probability density of X conditioned on Y , $\lambda[X|Y]$ denotes the mean occurrence rate of X given Y , IM denotes an intensity measure, EDP denotes engineering demand parameters, DM denotes damage measures, and DV denotes decision variables. This paper focuses on the damage and loss analyses. The complementary work to this project is described in a companion paper (Goulet et al. 2005) that focuses on the hazard and structural analyses.

The first step in this approach is the hazard analysis, which evaluates the seismic hazard for a particular facility, considering nearby faults, site distance, source-to-site conditions, facility location, facility design, etc. The ground shaking at the site is parameterized via an intensity measure. The hazard curve, $\lambda[IM|D]$, is the probability that at least one event will occur over time, t , with shaking at the site greater than the value IM . Some traditional intensity measures are peak ground acceleration and spectral acceleration at chosen periods (e.g., $S_a(T_i)$, the damped elastic spectral acceleration at the small-amplitude fundamental period of the structure). We use the latter in this work.

The second step is the structural analysis, in which the engineer creates a soil-foundation-structure (SFS) model of the facility in order to estimate the uncertain structural response. The response is measured in terms of a vector of engineering demand parameters ($EDPs$), conditioned on the intensity measure IM and design. Some examples of $EDPs$ are: directional peak transient interstory drift, directional peak diaphragm acceleration, peak plastic hinge rotation, and peak positive curvature in the beams. Note that the methodology allows for uncertainty in the structural models.

The third step of this methodology is the damage analysis. This step involves using cumulative distribution functions ($CDFs$) that express the probability that a facility component (e.g., beam, column, wall partition, etc.) is in or exceeds a particular damage state as a function of an EDP ; these $CDFs$ are referred to as fragility functions. The different damage states are indicative of the corresponding repair efforts needed to restore a facility component to an undamaged state. These fragility functions, compiled based on laboratory experiments, analytical investigation, expert opinion, or some combination, are used to create a probabilistic array of damage measures.

The DMs calculated in the analysis above are used in the final step of the PEER methodology, the loss analysis. This analysis, which is the focus of this paper, is the probabilistic estimation of structural performance conditioned on damage. Performance metrics that have been previously considered include repair cost, repair duration, and loss of life. The metric used in this study is repair cost. This final step of the methodology gives estimates of the mean annual frequency with which various levels of DV are exceeded; these can be used to inform a variety of risk-management decisions.

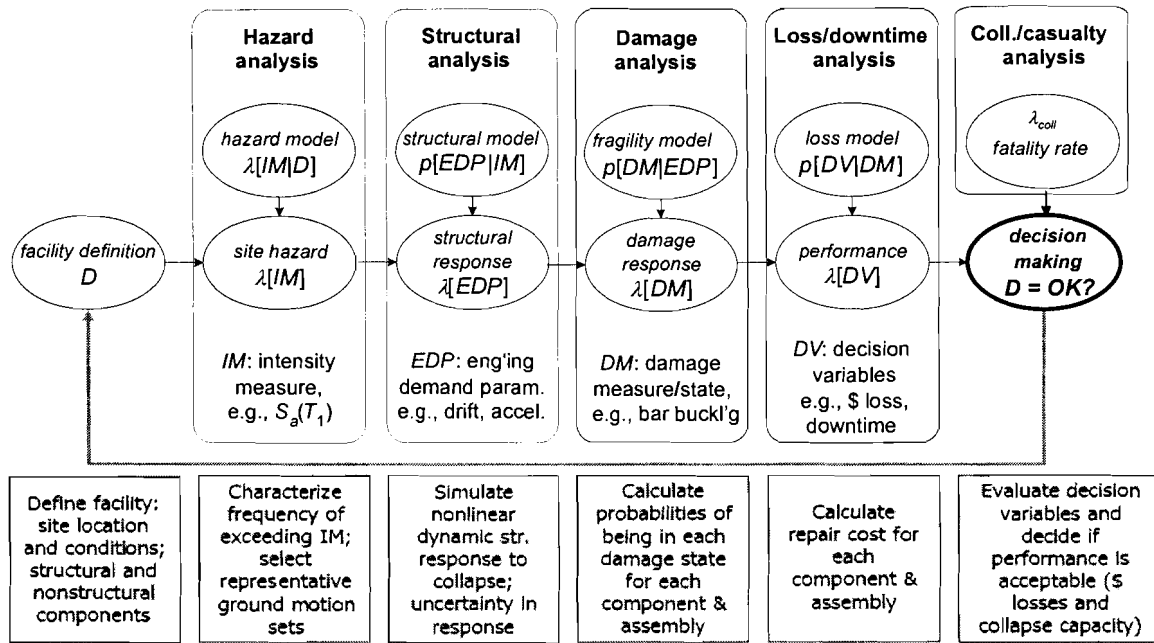


Figure 1: Schematic of PEER methodology (Porter 2003).

$$\lambda[DV | D] = \iiint p[DV | DM, D]p[DM | EDP, D]p[EDP | IM, D]\lambda[IM | D]dIMdEDPdDM \quad (1)$$

Building and Site Information

The purpose of the benchmark study was to evaluate the performance of new reinforced-concrete structures on a site that would be most typical of the range of seismic hazards in coastal California. The benchmark structure, a 4-story, reinforced-concrete moment-frame office building, is a hypothetical structure that was designed specifically for this study according to IBC-2003, ASCE7-02, and ACI 318-02. The selected site is the LA Bulk Mail Facility in Bell, CA (coordinates N33.996°, W118.162°), located south of downtown Los Angeles. More detailed information on the site hazard characterization, the record selection methodology, the structural modeling uncertainty, and the collapse analysis may be found in the companion paper (Goulet et al. 2005).

Site Information

The goal for this benchmark study was to locate the building on typical site conditions for an urban region within California. It was necessary to select a site where the ground motions would not be dominated by unusual features specific to the region (e.g. basin edge effects). Other factors were also considered and are described in detail in another report (Haselton et al. 2005). One would expect some effect of near-source ground motions, since the site is within 20 km of 7 faults. However, no single major fault produces near-fault motions that dominate the site hazard, and the contributions of near fault motions from the other faults are actually typical of the Los Angeles area. This site met the benchmark selection criteria and also had the advantage of available high quality geotechnical data from the Resolution of Site Response Issues from the

Northridge Earthquake program (ROSRINE 2005). The chosen benchmark site is located on deep sediments, mostly Quaternary alluvial deposits, near the middle of the Los Angeles Basin. The upper 30 m consist of sands and silts with traces of clay and cobbles with a corresponding average shear wave velocity V_{s-30} of 285 m/s (NEHRP soil category D).

Building Design

Several four-story office buildings were designed according to the 2003 International Building Code (ICC 2003). The plan and elevation views of the perimeter-frame designs are shown in Fig. 2; the space-frame designs have the same layout as the perimeter-frame ones, but with frames in every bay. Some variants of the perimeter- and space-frame buildings were designed with above-code strengths (125% of code required strength) and with strengths meeting the minimum code requirements. More details on the design of this benchmark structure can be found in the benchmark report (Haselton et al. 2005).

The building has a design seismic weight coefficient of 0.094g, corresponding to a calculated structural period $T_{code} = 0.80s^7$. The computed fundamental periods of the four designs range from 0.8 seconds to 1.3 seconds. Depending on the design, columns range in size from 18 in. x 24 in., to 30 in. x 40 in.; the beam dimensions range from 18 in. x 33 in., to 24 in. x 42 in. The designs were controlled by strength, the strong column-weak beam requirement, joint shear capacity provisions, and drift limitations (Haselton et al. 2005).

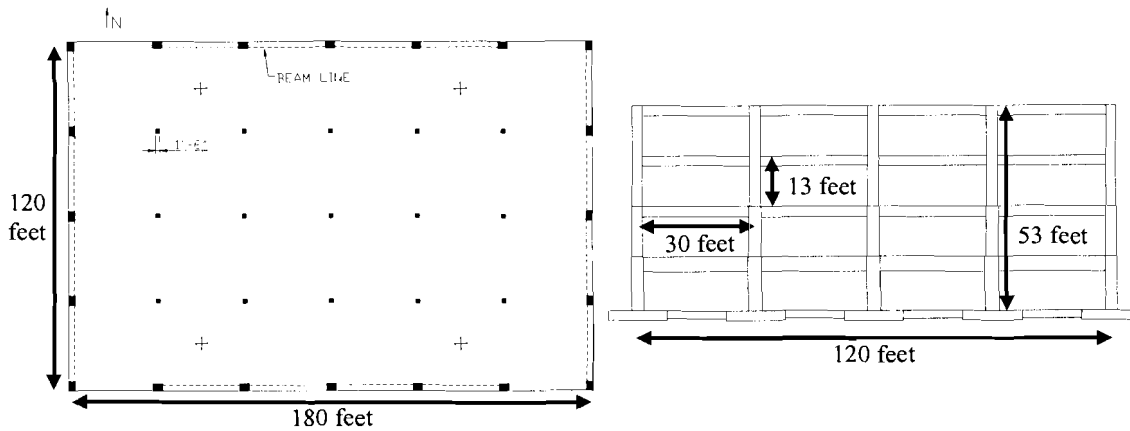


Figure 2: Plan and elevation of four-story office building.

For each building, a two-dimensional model was created of a typical four-bay frame in the N-S direction. For the perimeter-frame models, an equivalent gravity frame was modeled in series, to account for the additional strength and stiffness of the gravity system. For the space-frame models, the biaxial loading effects are not accounted for, as the models are only two-dimensional. To minimize the error induced from neglecting biaxial bending, the space frames were designed for strength demands only in the N-S direction (i.e., not biaxial strength demands).

⁷ This value includes the allowable 40% increase from the period computed by ASCE7-02 Eq. 9.5.5.3.2-1 (ASCE 2002).

Building Components Considered in Loss Estimates

In the PEER PBEE methodology, a detailed list of all structural and nonstructural components would normally be populated from a building's architectural and structural drawings. However, since the benchmark structure does not actually exist, architectural drawings were rendered for the benchmark study. It is necessary to account for the components that, if damaged, would account for most of the repair cost effort. Loss analysis studies from other studies (Beck et al. 2002) have shown that the building components that contribute the most to repair cost are structural members, drywall partitions and interior paint. Thus, this benchmark study focuses on these specific building components.

Fragility and Loss Distribution Functions

Fragility and cost distribution functions are created using experimental data, analytical investigation, expert opinion, or some combination. A review of loss estimation research shows that lognormal distributions adequately fit loss data and are commonly used for fragility and cost distribution functions (Porter 2000, Beck et al. 2002, Aslani and Miranda 2004). To fully describe a lognormal distribution, the median and logarithmic standard deviation are needed. Therefore, the median capacity and logarithmic standard deviations of capacity (defined in terms of the *EDP* value that causes an assembly to reach or exceed a given damage state) are used to create the fragility functions, and then to estimate damage. Also, the corresponding median unit repair costs and logarithmic standard deviations of cost are used to create the cost distribution functions, to estimate the loss.

Structural Components: Beams and Columns

There are various damage indices that are used to quantify damage of reinforced-concrete (RC) structural members. Williams et al., (1997) demonstrate that the modified Park-Ang Damage Index (*PADI*), given in Eq. (2), is a consistently reliable indicator of severe damage and structural failure. This result and available empirical data with clear definitions of damage states (Beck et al. 2002) are the motivation for using *PADI* as the *EDP* for the RC structural members in this benchmark study:

$$PADI = \frac{\Phi_m - \Phi_r}{\Phi_u - \Phi_r} \quad (2)$$

where Φ_m = maximum curvature attained during seismic loading

Φ_u = nominal ultimate curvature capacity

Φ_r = recoverable curvature at unloading

The fragility curves, shown below in Fig. 3, are used in the third step of PEER's PBEE methodology to relate the modified *PADI* values from the structural analysis to probabilities of exceeding the four levels of damage. Each level of damage corresponds to a specific repair effort: the light damage state is treated with epoxy injections, the moderate damage state corresponds to a jacketed repair, and the severe and collapse damage states correspond to replacement of the member. Note that no damage is also a damage state, known as "none".

Non-Structural Components: Drywall Partitions and Finish

The drywall partitions considered for the benchmark office building are 5/8" wallboard partitions on 3-5/8" metal stud at 16" centers with screw fasteners. The *EDP* used for the drywall partitions and finish is the peak transient drift ratio (*PTDR*). The fragility curves, shown in Fig. 3, were developed by Porter (2000) and are based on Rihal's (1982) in-plane racking tests of 8'-0 x 8'-0 building partitions. These fragility curves are used to relate the *PTDR* values from the structural analysis to probabilities of exceeding the two levels of damage. Each level of damage corresponds to a specific repair effort: the visible damage state corresponds to patching, and the significant damage state corresponds to replacement of the member.

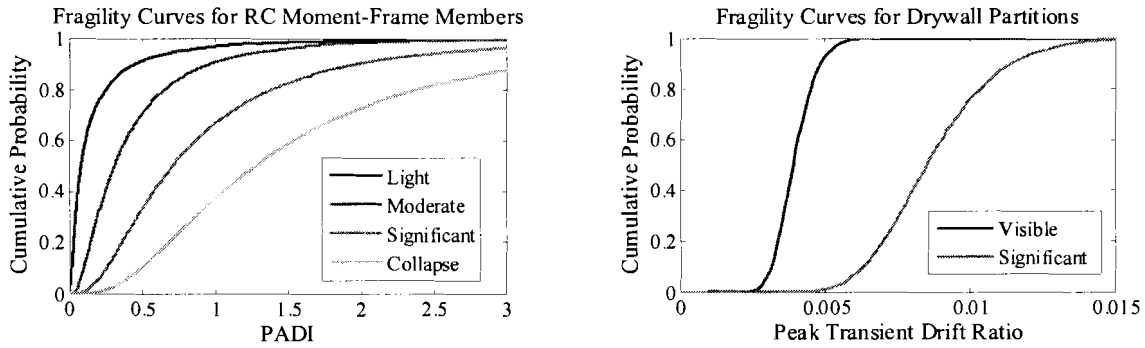


Figure 3: The left figure shows the fragility curves for RC moment-frame members and the right figure shows the fragility curves for the wallboard partitions.

Loss Results

The modular framework of the PEER methodology allows for straightforward software development. A MATLAB damage and loss analysis toolbox (MDLA) was created as part of this benchmark study to handle the damage and loss analyses portions of the PEER methodology. The inputs into the toolbox are: a database of fragility and cost distribution functions, tables of the damageable components of the benchmark building, and the hazard and structural analysis results. The outputs of the toolbox are the probability of exceedance of damage states for all damageable components in the structure and the *DVs* of the methodology described above. The *DVs* considered in this study are the repair costs to restore the building to an undamaged state.

Damage

The structural analysis results are combined with the damageable component fragility functions to compute the probability of reaching or exceeding damage state j , for a component of type i , conditioned on the structure not collapsing and on *IM*:

$$P[DM_{ij} | NC, im] = \int_{edp_i} P[DM_{ij} | edp_i] p(edp_i | NC, im) dedp_i \quad (3)$$

The first component of the integrand, $P[DM_{ij} | edp_i]$, is the probability of reaching or exceeding the damage states for a given building component, conditioned on *EDP* i appropriate

for component of type i (i.e., fragility function). The second component of the integrand, $p(edp_i | NC, im)$, is the probability distribution of EDP_i , conditioned on the structure not collapsing (NC) and on a given IM level. To evaluate this component, a lognormal distribution is used to fit the structural response data, as is done by other researchers (Miranda and Aslani 2003).

An example result of the damage analysis step is shown in Fig. 4, showing the average probability of reaching or exceeding each possible damage state for like components on each story level of the benchmark building. As expected, this figure shows that the probability of exceeding each damage state increases with increasing shaking intensity. Also, this figure shows that the probabilities of exceeding the more severe damage states are greater in the lower stories. The damage analysis results for all design variants considered in the benchmark study may be found in the final report (Haselton et al. 2005).

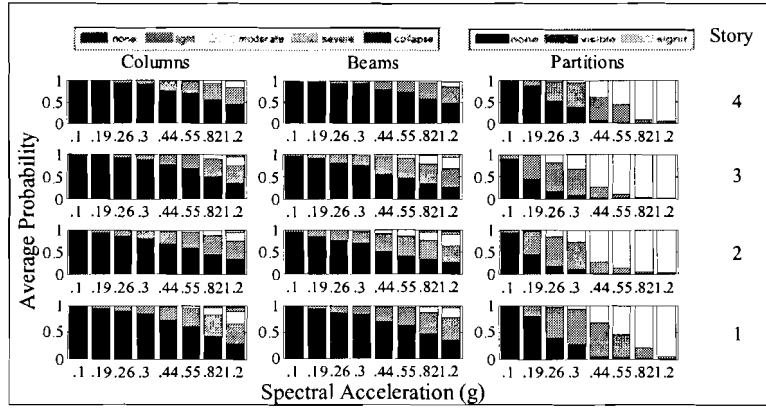


Figure 4: Average probabilities of damage per story level.

Vulnerability Functions

The vulnerability functions, a product of the last step of PEER's PBEE methodology, are the relationship between repair costs and shaking intensity level. The vulnerability functions are given by:

$$E[TC | im] = E[TC | NC, im] \cdot (1 - P[C | im]) + E[TC | C, im] \cdot P[C | im] \quad (4)$$

where $E[TC | im]$ is the expected total repair costs conditioned on IM and $E[TC | C, im]$ is the replacement cost of the structure. The expected total repair cost conditioned on the structure not collapsing and on IM , $E[TC | NC, im]$, is calculated by:

$$E[TC | NC, im] = (1 + C_{op}) \cdot C_i \cdot C_L \sum_{i=1}^{na} N_{u_i} \cdot E[RC_i | NC, im] \quad (5)$$

$$E[RC_i | NC, im] = \sum_{j=1}^{nds} E[RC_i | DM_{ij}] \cdot P[DM_{ij} | NC, im]$$

where C_{op} , C_i , C_L are the contractor overhead and profit, the factor for inflation, and the factor for location, respectively; na is the number of damageable component groups; N_{u_i} is the number of units in assembly group i ; RC_i is the repair cost for one unit in assembly group i ; and nds is

