Building-Specific Seismic Loss Assessment

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ABSTRACT

New procedures are being developed in the United States for building-specific seismic performance (loss) assessment. These procedures are substantially different from those currently used in practice. The new procedures will characterize performance in terms of direct economic loss, indirect economic loss and casualties rather than by building component deformations and accelerations. Uncertainty and randomness will be captured in every step of the performance assessment process. The paper summarizes the state-of-practice in seismic performance assessment, discusses the types of performance assessment made possible by the next-generation procedures, describes each step in the proposed loss assessment process and introduces a performance assessment calculation tool that can be used to perform the loss calculations.

Keywords: Performance, loss, assessment, seismic, fragility, damage, consequence

1. INTRODUCTION

The primary purpose of this paper is to introduce the next (second) generation procedures for seismic performance (loss) assessment in the United States. The methodology, which is described in detail in the 35% draft *Guidelines for the Seismic Performance Assessment of Buildings* (ATC, 2007) (hereafter termed the *Guidelines*), builds on the first generation deterministic procedures, which were developed in the ATC-33 project in the mid 1990s and recently published as an ASCE Standard: ASCE/SEI 41-06 *Seismic Rehabilitation of Existing Buildings* (ASCE, 2006). The procedures and methodologies described herein and in the draft *Guidelines* include an explicit treatment of the large uncertainties in the prediction of losses due to earthquakes. This formal treatment of uncertainty and randomness represents a substantial advance in performance-based earthquake engineering and a significant departure from the first generation deterministic procedures.

Figure 1 identifies the five basic steps proposed for a next-generation seismic performance assessment. Unlike prior assessment procedures that addressed either structural performance (e.g., ASCE/SEI 41-06) or repair cost, three measures of seismic performance are proposed in the draft *Guidelines*: 1) direct economic loss (repair cost), 2) indirect economic loss (downtime or business interruption), and 3) casualties (including injuries and death). Each of three performance measures is treated as a potential loss.

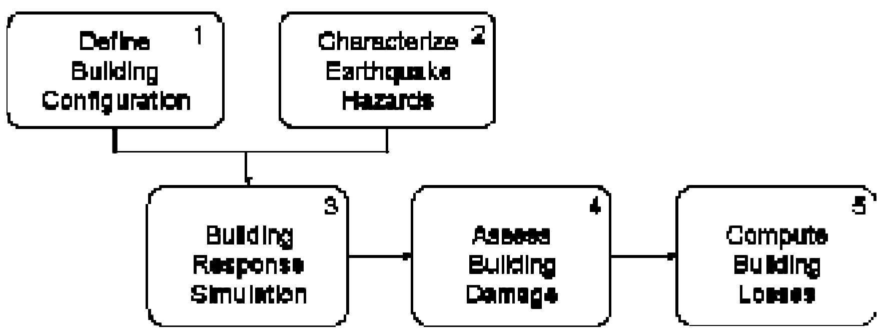


Figure 1 Proposed procedure for seismic loss assessment (ATC, 2007)

ASCE Standard ASCE/SEI 41-06 represents the state-of-practice in seismic performance assessment of buildings. The assessment method set forth in this Standard involves the first three steps of Figure 1, namely, 1) define a building frame in sufficient detail for structural analysis, 2) characterize the earthquake hazard in a format amenable to structural analysis, and 3) construct a mathematical model of the building as defined in step 1, analyze it for the earthquake hazard of step 2, and assess the adequacy of the building using component-level deformation and force-based acceptance criteria.

Four discrete performance levels are identified in ASCE/SEI 41-06: 1) operational, 2) immediate occupancy, 3) life safety, and 4) collapse prevention. Of the four levels, only two can be crisply defined: operational (for which there is little to no damage, requiring near-elastic response of the building frame, nonstructural components and building contents) and collapse prevention (the point of incipient building collapse). Performance-based assessment and design is accomplished by linking a performance level(s) to a seismic hazard level(s) as indicated in Figure 2. Simulation of building response is routinely performed with nonlinear static (pushover) analysis, which produces a relationship between seismic base shear and a reference (roof) displacement such as that shown in Figure 3.

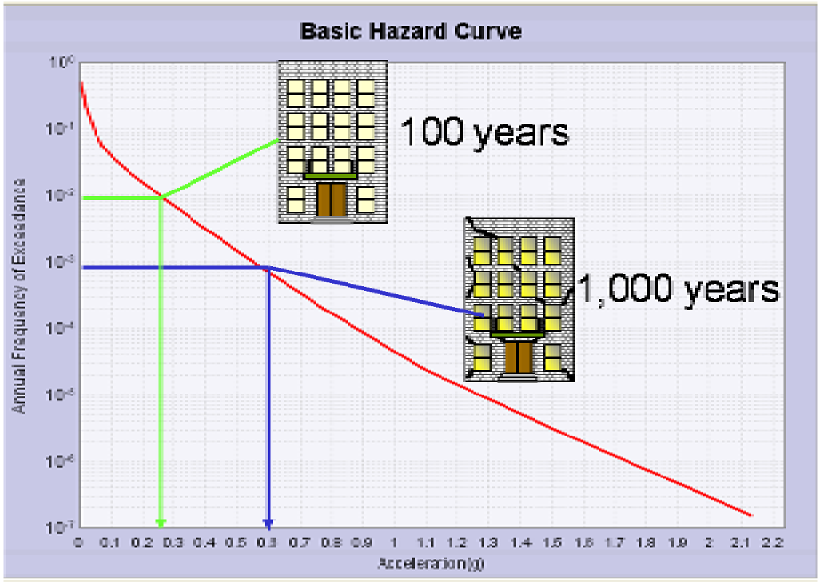


Figure 2. State-of-practice performance assessment

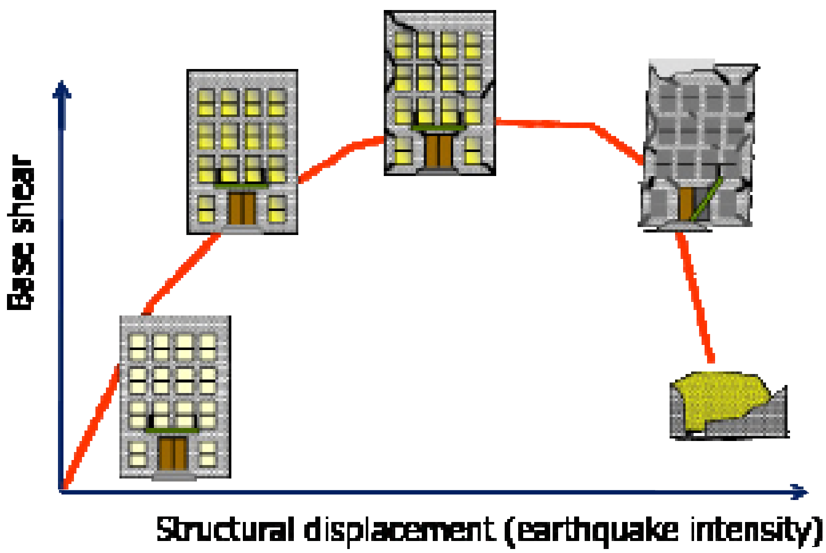


Figure 3. State-of-practice seismic performance assessment

Figure 3 illustrates the four *global* performance levels identified previously (from Left to Right: operational, immediate occupancy, life safety and collapse prevention) as a function of increasing displacement, which is used here as a surrogate for increasing earthquake intensity. (The fifth cartoon is that of a collapsed building.) Building analysis is performed for a given level of earthquake shaking to compute a single (deterministic) value of demand for each component in the building. Emphasis is placed on demands on structural components. Default acceptance criteria are provided in ASCE/SEI 41-06 for typical modern and archaic materials and structural details as a function of the user-specified global performance level. Global building performance is tied to component performance, with building performance characterized by the poorest performing structural component(s). (For example, consider a building composed of 100 structural components. If for a given level of earthquake shaking, 97 of the components met the acceptance criteria for immediate occupancy or better, and the remaining 3 components met the (lower) life safety acceptance criteria, building performance would be described as only life safe.)

The writers of the predecessor documents to ASCE/SEI 41-06 recognized that a description of building performance based primarily on the poorest performing structural component was both misleading and incorrect. However, no alternate procedures for loss aggregation were available at that time and the profession's understanding of the seismic response of nonstructural components and building contents was modest at best and insufficient to make clear statements about building performance.

Figure 4 (after Miranda) was developed using information prepared for the HAZUS project (NIBS, 1997) and it is reproduced here to illustrate the percentage investment in structural components, nonstructural components and building contents for three types of buildings. Although the percentage investment in structural framing is relatively small in all three building types, a state-of-practice performance assessment would focus on this framing and by-and-large ignore the nonstructural components and building contents that often suffer significant damage (and loss) for minor and moderate earthquake shaking. Such components and contents are often ignored because there is insufficient knowledge of how their seismic response relates to the global performance levels introduced previously.

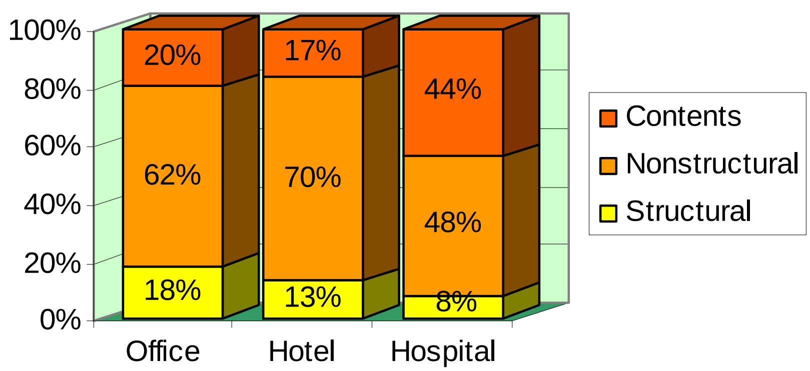


Figure 4. Investments in building construction (after Miranda and NIBS, 1997)

Many of the shortcomings of the first generation procedures for seismic performance assessment were understood clearly by the developers of the procedures but could not be addressed because the required framework, knowledge and assessment procedures did not exist. A key shortcoming of the procedures first published by the Applied Technology Council in the mid 1990s, and now documented in ASCE/SEI 41-06, was the use of an engineering-oriented vernacular and assessment framework that did not engage decision makers: decision makers talked quantitatively in terms of dollar loss, business interruption and casualties whereas structural engineers described performance using qualitative and poorly defined metrics such as life safety.

2. SECOND GENERATION PERFORMANCE-BASED EARTHQUAKE ENGINEERING

In 1997, the US National Science Foundation funded the Pacific Earthquake Engineering Research (PEER) Center (www.peer.berkeley.edu) to develop second (next) generation tools and procedures for performance-based earthquake engineering, and in doing so, to address the shortcomings identified with the first generation procedures described previously. The subsequent research work at the PEER Center enabled the Federal Emergency Management Agency (FEMA) to commence development in 2002 of the *Guidelines for the Seismic Performance Assessment of Buildings* that was introduced previously. The remainder of this paper focuses on these *Guidelines*, which are now available as a 35% complete draft (ATC, 2007).

The three types of performance assessment that can be performed using the draft *Guidelines* are described below. The five steps proposed for seismic performance assessment and identified in Figure 1 are summarized. The performance calculation assessment tool, PACT, developed by the ATC-58 project team that is writing the *Guidelines* is described. The interested reader can download the 35% draft *Guidelines* and the β version of PACT from http://www.atcouncil.org/atc-58.shtml.

2.1 Probabilistic framework for the second generation procedures

The probabilistic framework that serves as the technical basis for the procedures described in the *Guidelines* is based on a methodology developed by the PEER Center researchers (Moehle and Deierlein, 2006). The framework enables the calculation of the probability of loss, L, exceeding a value, l, using either:

$$P(L > l) = P(L > l \mid E = e) \tag{1a}$$

$$P(L > l) = \int_{\lambda} P(L > l \mid E = e)\, d\lambda \tag{1b}$$

where E is an earthquake intensity variable (e.g., spectral acceleration at the first mode period), e is a value of the earthquake intensity (e.g., 0.37g), $P(L > l \mid E = e)$ is the probability of loss exceeding l for an earthquake intensity of e, $\lambda(e)$ is the mean annual frequency of exceeding e, and the integration is performed over a range of λ. Loss can be computed for each performance measure using one or more of three characterizations of seismic hazard: a user-specified *intensity* of earthquake shaking, a user-specified *scenario* of earthquake magnitude and site-to-source distance, and a *time-based* representation considering all possible earthquakes.

The calculation of the probability that the loss exceeds l for earthquake shaking of intensity e involves a number of steps that are illustrated in Figure 1, are summarized below and are described in detail in Chapters 4, 5 and 6 of the *Guidelines*. In brief, the PEER framework involves a) the calculation of building response, including both structural and nonstructural components for a given value of e, b) the assessment of damage to components in the building for the calculated building response, and c) the transformation of the building damage state into loss.

Intensity-based and scenario-based loss computations are performed using (1a). Equation (1b) is used for time-based assessments and the integration is performed over a range of mean annual frequency of exceedance, though, as described later, the integration is replaced by a discrete summation over intervals of earthquake intensity. (Scenario-based assessments could be performed using (1b) but λ in this instance would represent the distribution of earthquake intensity conditional on a user-selected combination of earthquake magnitude and site-to-source distance.) More information on each type of assessment follows.

2.2 Types of performance assessment

Intensity-based assessment

An intensity-based performance assessment provides a distribution of the probable loss, given that the building experiences a specific intensity of shaking. In the *Guidelines*, ground shaking intensity is represented by a 5% damped, elastic acceleration response spectrum. Intensity could also include representation of permanent ground displacements produced by fault rupture, land slide, liquefaction, and compaction/settlement. This type of assessment could be used to answers questions like: 1) What is the probability of loss in a given range, if the building experiences a ground motion of a specific intensity?, and 2) What is the probability of direct economic loss greater than $1 M, if the building experiences a ground motion represented by a smoothed spectrum with a peak ground acceleration of 0.5 *g*?"

For intensity based assessments, the value of the earthquake intensity variable, *e*, is deterministic: *e* takes on a single value of spectral acceleration. Figure 5 presents results of four sample intensity-based assessments. Results are presented as cumulative probability distributions for direct economic loss in a hypothetical building for four independent intensity levels, I1 through I4, where intensity I2 is greater than intensity I1, etc. The figure plots the probability that the total repair cost exceeds a specified value of total repair cost (trc) versus trc. As a sample interpretation, for shaking intensity I4, there is a 50% probability that the total repair cost will exceed $1.8 M and a 90% probability that the total repair cost will exceed $0.9 M.

Scenario-based assessment

A scenario-based performance assessment is similar in many regards to an intensity-based assessment and enables an estimate of loss, given that a building experiences a specific earthquake, defined as a combination of earthquake magnitude and distance of the site from the fault on which the earthquake occurs. This type of assessment could be used to answer the following types of questions: 1) What is the probability of more than ten casualties from an M 6 earthquake on the fault ten kilometers from the building site? and 2) What is the probability of repair costs exceeding $5 M if my building is subjected to a repeat of the 1906 San Francisco earthquake?

Scenario assessments may be useful for decision makers with buildings located close to one or more known active faults. For scenario-based assessments, the earthquake intensity variable, *E*, is a random variable that is described by a probability distribution (say $\hat{e}$). Loss can be computed using either of the equations in (1), depending on how the uncertainty in the earthquake shaking intensity is addressed. The product of a scenario-based assessment is a *single* loss curve, such as one of the curves in Figure 5.

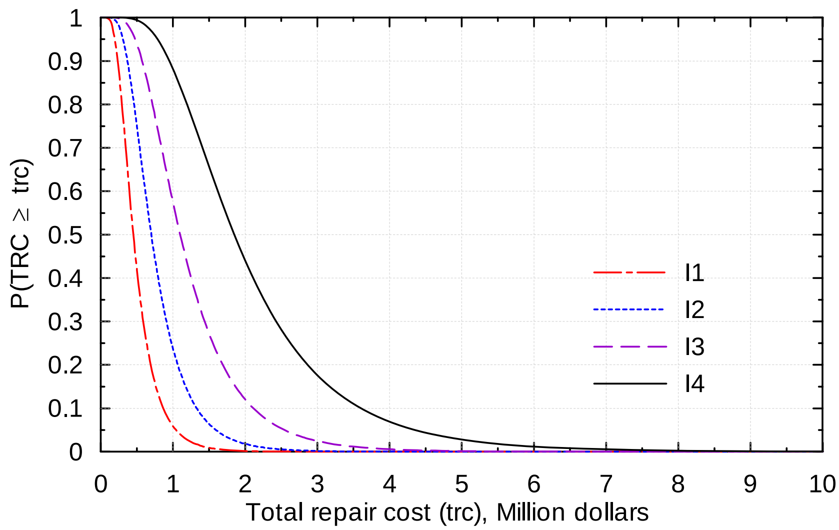


Figure 5. Example cumulative probability distributions for loss exceeding a specified value for a hypothetical building at four ground motion intensities (ATC, 2007)

Time-based assessment

A time-based assessment is an estimate of the probable earthquake loss, considering all potential earthquakes that may occur in a given time period, and the mean probability of occurrence of each. A time-based assessment could be used to answer the following types of questions: 1) What is the mean annual frequency of earthquake-induced direct economic loss resulting from damage to my building and contents exceeding $300,000?, 2) What is the mean frequency of losing the use of my building for more than 30 days from an earthquake over its fifty-year life? and 3) What is my average expected loss (in direct dollars, downtime, lives) each year I own the building?

For a time-based assessment, the earthquake-intensity variable is described by a seismic hazard curve, which plots the relationship between earthquake intensity, *e*, and the mean annual frequency of exceedance of *e*, $\lambda(e)$. Loss curves are developed for intensities of earthquake shaking that span the intensity range of interest and which are then integrated (summed) over the hazard curve to construct an annualized loss curve of the type shown in Figure 6. The mean annual total loss is computed by integrating the area under the loss curve, which is equal to approximately $37,900 in this example. The accuracy of the annualized loss curve is a function of the number of intervals of earthquake intensity used in the computation.

2.3 Methodology for performance assessment

The five basic steps in a seismic performance assessment conducted using the *Guidelines* are identified in Figure 1 and are described in this section. Step 1 requires the user to define the building in sufficient detail to compute losses. Step 2 involves the appropriate characterization of the seismic hazard, which depends on the type of assessment. Step 3 involves analysis of the building, described in Step 1, subjected to the hazard of Step 2, to predict its response, that is, to compute the accelerations, forces, displacements and deformations that serve as demands on the building's

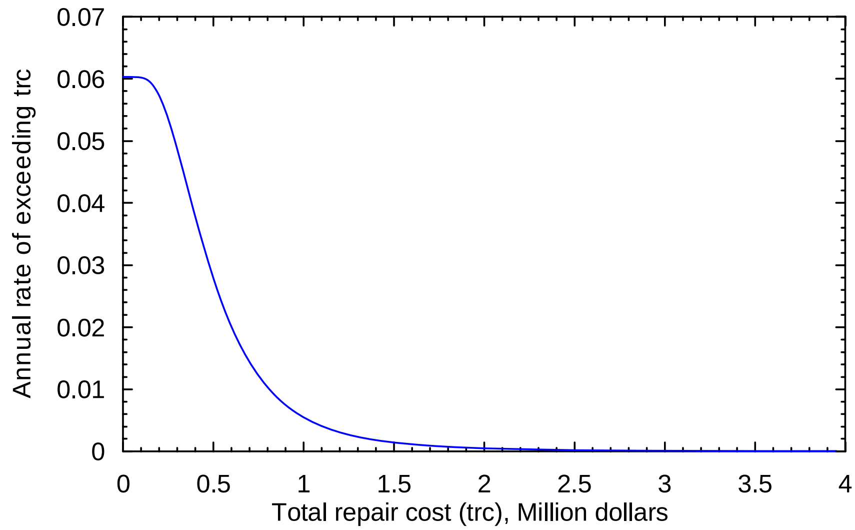


Figure 6. Distribution of mean annual total repair cost (ATC, 2007)

components and contents. Damage to structural and nonstructural components is assessed in Step 4 using the demands computed in Step 3 and fragility functions that are based on the user-specified definition of the building's components (Step 1). Step 5 involves the computation of loss using consequence functions (and a hazard curve for time-based assessment).

Step 1: Building definition

The first step involves the definition of the building's location, configuration and characteristics pertinent to response in earthquakes, including a) site location: identifying the seismic hazard and ground motion intensity; b) site conditions: identifying how local soil conditions will affect the earthquake ground motion intensities and characteristics; c) construction: providing information on the structural framing (seismic and gravity) and nonstructural components and systems; and d) occupancy: providing information on the tenants and contents in the building.

It is not possible to define these four characteristics precisely. For example, it is not possible to define exactly the following at the time of a future earthquake: a) the total number of persons that will be present in the building, b) the locations and value of all furnishings, c) the age and condition of the mechanical equipment, d) the subsurface conditions, and e) the strength, stiffness, ductility and damping of the framing system. However, it is possible to make reasonable estimates of the likely value of the key characteristics that affect performance together with estimates of their possible variations.

Information on the site location and the site conditions are required to establish the seismic hazard for scenario- and time-based assessments and will likely be used to develop a response spectrum for an intensity-based assessment. Information on the site conditions is also important for the selection of ground motions for response-history analysis. Construction information, either as proposed, as existing, or a combination of both (for retrofit computations), is required to establish the seismic and gravity load-resisting systems and enable the development of a numerical model of the building that is suitable for analysis and the selection of appropriate structural-component fragility curves to compute damage and losses once the demands are known. Occupancy information is required so that the user can a) identify likely inventories and quantities of nonstructural components and contents in the building; b) assign fragility curves to the components and contents, to enable calculations of damage and associated losses; and c) to evaluate casualty and downtime losses associated with occupants and the building function.

Step 2: Characterization of earthquake shaking

A primary input into the performance assessment process is the definition of the earthquake effects that cause building damage and loss. In the most general case, earthquake hazards can include ground shaking, ground fault rupture, liquefaction, lateral spreading and land sliding. Each of these can have different levels of severity, or intensity. Generally, as the intensity of these hazards increases, so also does the potential for damage and loss. In the *Guidelines*, only the effects of earthquake shaking are considered for loss computations although the framework could be easily modified to accommodate other earthquake hazards.

There are two ways to represent seismic hazard for intensity, scenario and time-based assessments, namely, 1) a response spectrum (spectra) for linear static analysis, and 2) families of earthquake histories for nonlinear response-history analysis. One acceptable set of procedures for characterizing seismic hazard (and selecting and scaling earthquake ground motions to represent the hazard for nonlinear response analysis) is presented in Chapter 5 of the *Guidelines*.

Step 3: Building response simulation

The third step in the process of Figure 1 is to perform analysis of the building defined in Step 1 for ground shaking consistent with the seismic hazard of Step 2. For analysis, the building defined in Step 1 must be transformed into a numerical model of a complexity that will be dictated by a) the availability of information, b) the degree of accuracy required from the loss computation, and c) the time and effort available to the user. The least accurate estimates of structural demand (smallest confidence in the answer) will result from the use of approximate linear models of the framing system and the simplest characterizations of seismic demand. The most accurate estimates of demand will be computed using detailed nonlinear models of the vertical and horizontal framing systems, foundations and subsurface materials and rigorous characterizations of building responses.

Either linear static or nonlinear response-history analysis will be used to compute peak demands. Since both a building’s mechanical characteristics and the earthquake shaking are highly uncertain, it is not possible to calculate precise (deterministic) values of these demands. Instead, it is necessary to predict a statistical distribution of the likely values of demands, considering the possible variation in earthquake intensity, ground motion characteristics, and structural modeling uncertainty (associated with variations in the building’s properties and the extent to which these are accurately captured by an idealized analysis model). The distributions in each demand parameter are then used to assess damage and estimate loss as described in the following subsections. One consistent set of acceptable procedures to capture the distributions in the seismic hazard and to perform the response simulations are described in Chapters 5 and 6 of the *Guidelines*, respectively. (The linear static method of analysis presented in the *Guidelines* is most different from those presented in seismic design codes and ASCE/SEI 41-06 and involves computations of story drift and floor accelerations using roof displacement and ground acceleration, respectively, that are then modified using equations developed by regression analysis of data mined from the nonlinear analysis of regular 3-, 5- and 9-story buildings (Huang et al., 2008).)

Step 4: Assessment of damage

Introduction

In Step 4, the response data from the structural analysis of Step 3 is used together with information on the building's configuration to calculate the possible distribution of damage to structural and nonstructural components and building contents. Each analysis will produce a vector of response quantities that can be applied as demands to one or more structural and nonstructural components in the building. Component- or framing-system-specific fragility functions are then used to characterize damage for the demands computed by the analysis. The prediction of damage, measured here using damage states, is also uncertain, even for a specific value of the demand. The assessment of damage given demand is performed using fragility curves that relate the probability of damage to structural demand parameters (e.g., story drifts, floor accelerations, or other response quantities).

Seismic fragility curves

Each structural and nonstructural component in a building will have a unique probability of sustaining damage in an earthquake, based on its construction characteristics, location in the building and the response of the building to earthquake shaking. The loss computation methodology described herein utilizes fragility curves to relate the probability of damage to demand, where demand can be measured using any useful response quantity, including story drift, floor acceleration, component force, and component deformation.

To enable computations of loss, a series of discrete damage states must be defined for each component in the building. These damage states must be meaningful in terms of the considered performance measure (i.e., repair costs, downtime and casualties). Importantly, those damage states that are meaningful for one performance measure (e.g., direct economic loss) may not be useful for another performance measure (e.g., casualties) and alternate damage states must be identified.

In the *Guidelines*, fragility curves are required for all measures of performance but are described here using the performance measure of direct economic loss (repair cost). Fragility curves are required for each component in a building that might contribute to the loss, and for each type of loss, to permit performance assessment using the procedures set forth in the *Guidelines*.

Damage states for direct economic loss are defined in terms the degree or scope of repair. In reality, damage generally occurs as a continuum and not as a series of discrete states. For example, consider damage to a steel beam measured using the amplitude of flange local buckling: the amplitude of the buckling is a continuous function of beam deformation. However, the cost of repair of this damage is not a continuous function of flange buckling amplitude: it makes no difference whether the buckling amplitude is 1/4” or 3/8” as the repairs will be very similar and the costs essentially identical. Conversely, modest increases in the level of damage can trigger large increments in construction activity and cost. For example, at an amplitude of 1/16”, no repair may be required, but at an amplitude of 1/8”, heat straightening of the beam flange may be required, which would require substantial work and cost.

Figure 7 presents a sample family of fragility curves for a special steel moment frame connection. Three damage states are used, where the damage states are defined using discrete and well separated (in terms of cost) states of repair: DS_1 (flange and web local buckling in the beam requiring heat straightening of the buckled region); DS_2 (DS_1 damage and lateral-torsional distortion of the beam in the hinge region requiring heat straightening and part replacement of the beam flange and web in the hinge region and the attendant construction work to other structural and nonstructural components; and DS_3 (low-cycle fatigue fracture of the beam flanges in the hinge region requiring replacement of a large length of beam in the distorted/fractured region and the attendant construction work to other structural and nonstructural components).

Fragility curves like those of Figure 7 plot the probability that a component or system will be damaged to a given damage state or a more severe damage state as a function of demand, expressed here using story drift ratio. Each curve is represented by a lognormal distribution with a median (50th percentile) demand θ_{DS_i} and a dispersion β_{DS_i} . The dispersion is associated solely with the onset of the associated damage as a function of building response (i.e., demand) and is independent of the uncertainty associated with the intensity of shaking or the prediction of demand. The dispersion reflects variability in construction and material quality, as well as the extent that the occurrence of damage is totally dependent on the single demand parameter and the relative amount of knowledge or data on the response of the component.

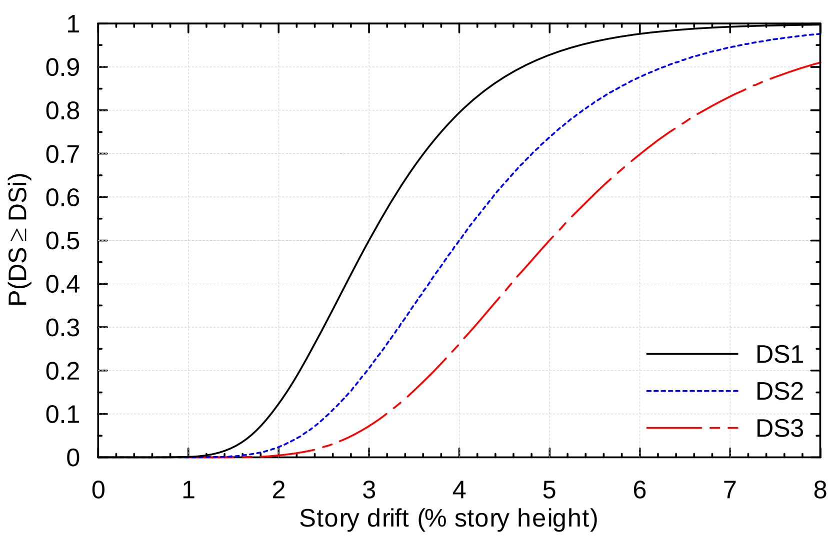


Figure 7. Example family of fragility curves for special steel moment frames (ATC, 2007)

Step 5: Computation of losses

Monte Carlo procedures for loss computation

Monte Carlo type procedures are used to develop mean estimates of casualties, direct economic losses and downtime as well as information on the possible variation in these losses. In Monte Carlo analysis, each of the factors that affect performance, namely, earthquake intensity; structural response as measured by demand parameters; damage, as measured by damage states; and consequences (losses), are assumed to be random variables, each with a specific probability distribution defined by a median value and its dispersion.

A large set (100s) of simulations is required per intensity level to generate a loss curve using Monte Carlo procedures. Each simulation represents one possible outcome of the building experiencing the given intensity of motion. The large set of simulations can be generated a) directly by a large number of analyses, or b) indirectly by statistical manipulation of the results of a smaller number of analyses. The *Guidelines* presents one acceptable set of procedures for generating a large number of simulations through statistical manipulation of a relatively small number of structural analyses (Yang et al., 2006).

Each simulation of response enables the development of a building damage state and the calculation of a single value of the performance measure (loss). By repeating the simulations and calculations many times, a distribution of loss (repair cost, downtime or casualties) is constructed for the chosen intensity of earthquake shaking. Sorting the losses in ascending or descending order enables the calculation of the probability that the total loss will be less than a specific value for a given intensity of shaking, producing a loss curve (see the sample curves in Figure 5). A loss curve can be used to determine: 1) Median performance: the number of casualties, direct economic loss and downtime loss exceeded by half of the realizations; there is a 50% chance that actual earthquake losses will be less than or greater than the median; 2) Mean performance: the average (expected) number of casualties, direct economic loss and downtime values obtained from all of the realizations; and 3) Dispersion: a measure of the amount that the building performance, as measured in casualties, direct economic loss and downtime, can be greater or less than the median values.

Building damage states and consequence functions

A building damage state is developed for each earthquake analysis or simulation. The building damage state is a complete description of the repair actions required to return a building to its pre-earthquake condition, the potential restrictions to occupancy and the risks to occupant safety. It is assembled from the story- or component-level damage states of Step 4 using the corresponding fragility functions, the vector of demands from the simulation, and the likelihood of total building collapse (for occupant risk). Consequence functions, which are distributions of the likely consequences of a building being damaged to a given state, are then used for the purpose of assembling single estimates of repair cost, casualties and downtime. Families of consequence functions are developed for each performance measure and these families will generally differ across types of buildings. The general functions are complex and uncertain and must be simplified using heuristic procedures and approximations for practical implementation. A sample consequence function for cost of repair is presented in Figure 8.

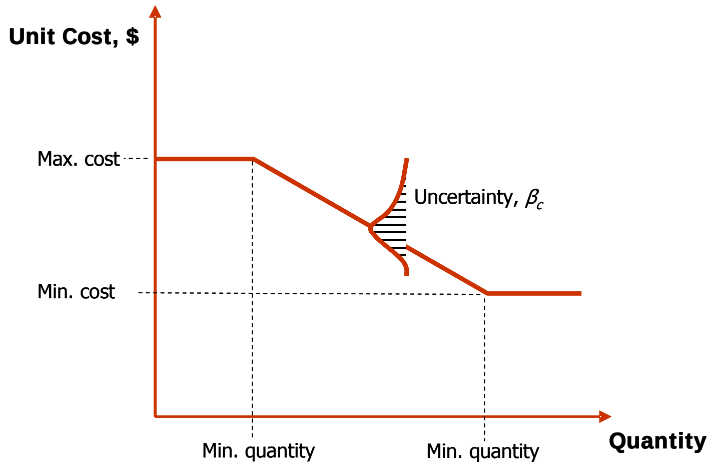


Figure 8. Sample consequence function for cost of repair (ATC, 2007)

A building damage state, for purposes of direct economic loss calculations, includes a detailed description of the condition of the building in terms of the required repairs. This description could be given to a contractor to form the basis for an estimate of the costs to repair the building and replace the damaged contents. When a contractor makes such an estimate, the unit costs applied to the various repair quantities depend on the total quantities of basic repair measures. In some instances (e.g. scaffolding, protection of finishes, clean-up), costs are distributed to more than a single repair measure. Contractors' overhead and profit depend on the total amount of work and the type of tradesmen and subcontractors required. In effect, the contractor applies a *direct economic loss consequence function* to the damage to calculate the loss. The consequence functions for direct economic losses use the building damage state to determine the need for shoring, staging, finish protection, cleaning, and other general condition costs; the costs associated with contractor overhead and profit and indirect project costs including design services, fees and permits as well as the costs of the actual labor and materials associated with the individual repairs required.

Consequence functions for direct economic loss should account for the effect of quantities on unit price. These are of the general form illustrated in Figure 8 above. For small quantities the unit cost is constant at a maximum value. Beyond a certain quantity the cost diminishes as the contractor can take advantage of economies of scale until a minimum unit cost for large quantity repairs is reached. Since costs are subject to uncertainty from market conditions, contractor bidding strategy, and other factors, unit costs are assigned a median value and dispersion, β_c.

<u>Loss as a function of types of assessment</u>

The product of intensity-based and scenario-based assessments is a loss curve of the type shown in Figure 5. The key difference between the intensity- and scenario-based assessments is that a distribution of earthquake shaking conditioned on a given earthquake magnitude and site-to-source distance is used for a scenario assessment.

The product of a time-based assessment is a curve of the type shown in Figure 6, which plots the total repair cost versus the annual rate of exceeding the total repair cost. The curve shown in Figure 6 can be constructed using the results of a series of intensity-based assessments and the appropriate seismic hazard curve. A sample seismic hazard curve is shown in Figure 9, where the annual frequency of exceeding an earthquake intensity, $\lambda(e)$, is plotted versus the earthquake intensity, e, where the typical earthquake intensity is spectral acceleration at the first mode period of the building. Equation (2) is used to calculate the annual frequency that the loss L will exceed a value l:

$$P(L > l) = \int_{\lambda} P(L > l \,|\, E = e)\, d\lambda(e) = \sum_{i=1}^{n} P(L > l \mid E = e_{Ii})\Delta\lambda_i \qquad (2)$$

where most terms are defined below (1). For the summation, the spectral range of interest is split into n equal intervals, Δe_i, the midpoint intensity in each interval is e_{Ii}, and the annual frequency of earthquake intensity in the range Δe_i is $\Delta\lambda_j$. Figure 9 defines Δe_i, e_{Ii} and $\Delta\lambda_j$ for the sample hazard curve and n = 4. (The small value of n is chosen to simplify the figure).

For a time-based assessment, a series of n intensity-based assessments are performed at e_{I1} through e_{In}, where the user-selected range of earthquake intensity is from no damage (small e) through collapse (larger e). The number n is selected by the user. Earthquake intensity at intensity e_{I1} is assumed to represent all shaking in the interval Δe_1, and so on. The product of the n intensity-based assessments is n loss curves of the type shown in Figure 5. The annual frequency of shaking of intensity e_{Ij}, $\Delta\lambda_j$, is calculated directly from the seismic hazard curve. A sample calculation is shown in Figure 9 for interval Δe_1 for which $\Delta\lambda_1 = 0.054$. Figure 6 is constructed by multiplying each loss curve by the annual frequency of shaking in the interval of earthquake intensity used to construct the loss curve, and summing the annual frequencies for a given value of the loss.

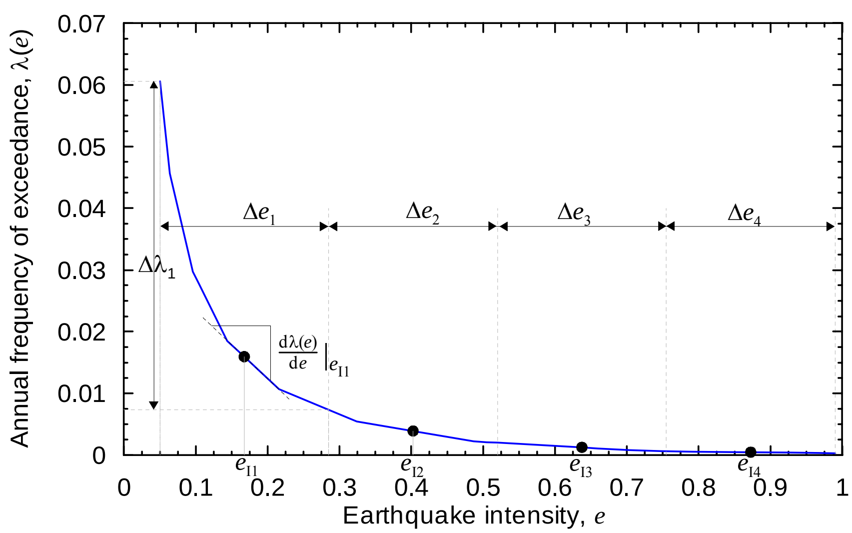


Figure 9. Seismic hazard curve and time-based loss calculations

2.4 Performance Assessment Calculation Tool (PACT)

A Performance Assessment Computation Tool (PACT) has been developed by the project team to implement the loss computations described in Section 2.3. Some sample PACT screen captures are presented below to illustrate its use. A β version of PACT is available for download from the project website but its utility is limited to two framing systems (special steel moment frames and light timber shear walls) and two occupancies (commercial office and residential housing) at this time. The PACT code is open source and it will be possible to develop alternative software to perform these calculations.

Figure 10 is a screen capture illustrating how a building is defined in a preliminary sense. Figure 11 identifies some normative quantities in the building based on information input by the user, including occupancy type (see Figure 10). Figure 12 presents fragility data for a special steel moment-resisting frame. The default quantities and values shown in the screen captures of Figures 11 and 12 can be adjusted by the user. Figure 13 shows how building response data (3 story drifts and 4 ground/floor accelerations for each of 11 earthquake sets) are input to PACT, noting that all building response simulations are performed outside of the loss assessment tool. Figure 14 is a sample loss curve for an intensity- or scenario-based assessment. Figure 15 is a sample loss curve for a time-based assessment. Importantly, these loss curves can be de-aggregated by performance group (a grouping of like components subjected to identical demands, for example, all second floor suspended ceilings) to identify the key contributors to loss—information that could then be used to adjust a building design.

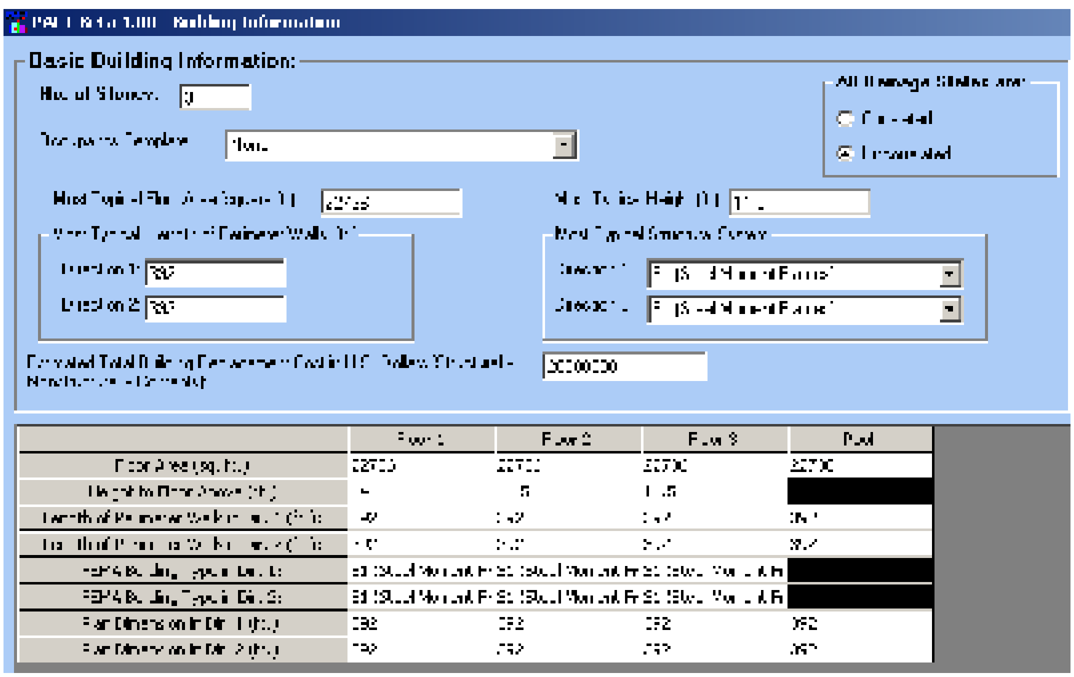
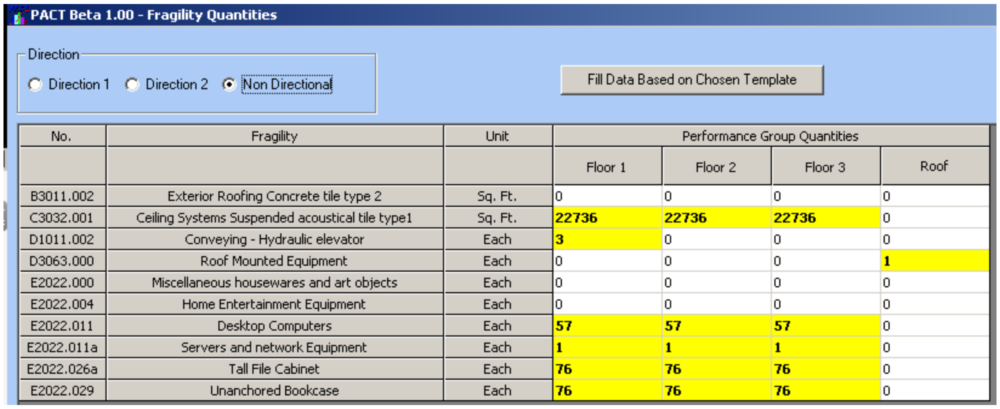


Figure 10. PACT screen capture illustrating building definition

3. CONCLUDING REMARKS

The next-generation tools and procedures for performance-based earthquake engineering will enable building-specific computations of direct economic loss (repair cost), indirect economic loss (downtime or business interruption) and casualties for intensity, scenario and time-based representations of seismic hazard. Preliminary



No.	Fragility	Unit	Performance Group Quantities			
			Floor 1	Floor 2	Floor 3	Roof
B3011.002	Exterior Roofing Concrete tile type 2	Sq. Ft.	0	0	0	0
C3032.001	Ceiling Systems Suspended acoustical tile type1	Sq. Ft.	22736	22736	22736	0
D1011.002	Conveying - Hydraulic elevator	Each	3	0	0	0
D3063.000	Roof Mounted Equipment	Each	0	0	0	1
E2022.000	Miscellaneous housewares and art objects	Each	0	0	0	0
E2022.004	Home Entertainment Equipment	Each	0	0	0	0
E2022.011	Desktop Computers	Each	57	57	57	0
E2022.011a	Servers and network Equipment	Each	1	1	1	0
E2022.026a	Tall File Cabinet	Each	76	76	76	0
E2022.029	Unanchored Bookcase	Each	76	76	76	0

Figure 11. Normative quantities of building components

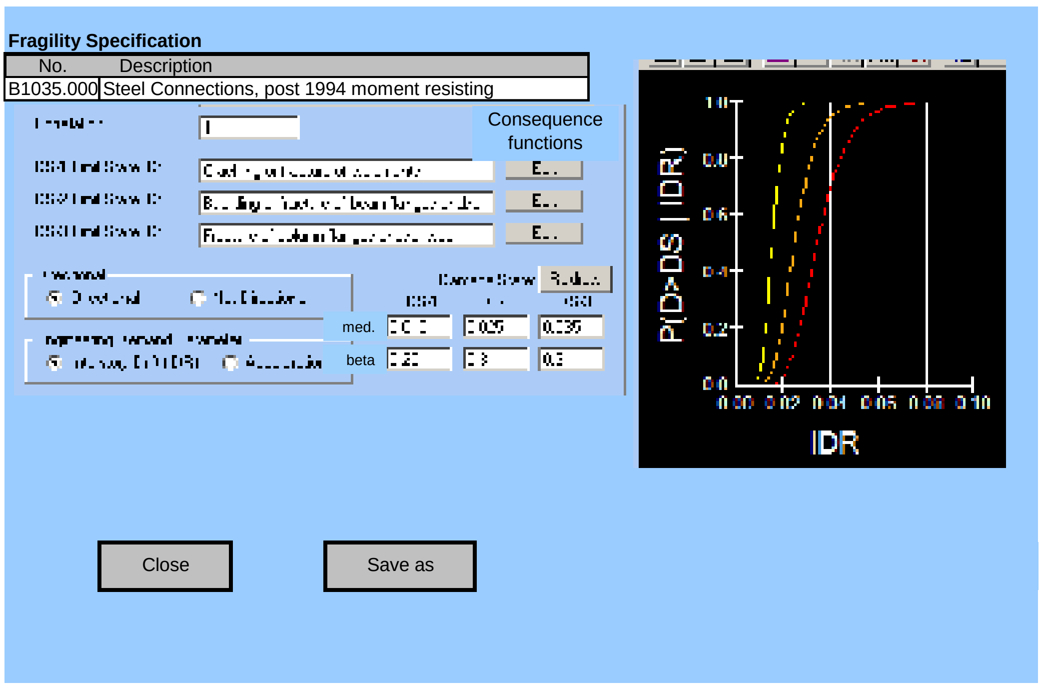


Figure 12. Fragility data for special steel moment-resisting frames

documentation of these tools and procedures is available in the 35% draft *Guidelines for the Seismic Performance Assessment of Buildings*. The procedures set forth in the *Guidelines* represent a substantial departure from the deterministic tools and procedures used at this time because uncertainty and randomness is captured explicitly in every step of the proposed procedures. Fragility functions, damage states and building-level consequence functions, most of which are unfamiliar to structural engineers, are used in the proposed procedure to compute losses. Much additional information and a β version of a loss calculator, PACT, can be downloaded from the ATC-58 project website: http://www.atcouncil.org/atc-58.shtml.

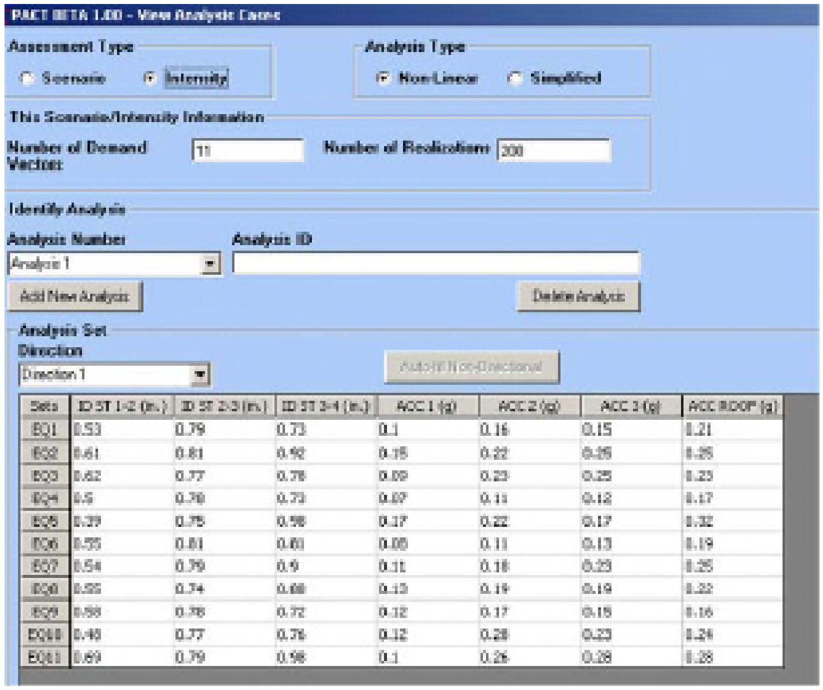


Figure 13. Building response data input to PACT

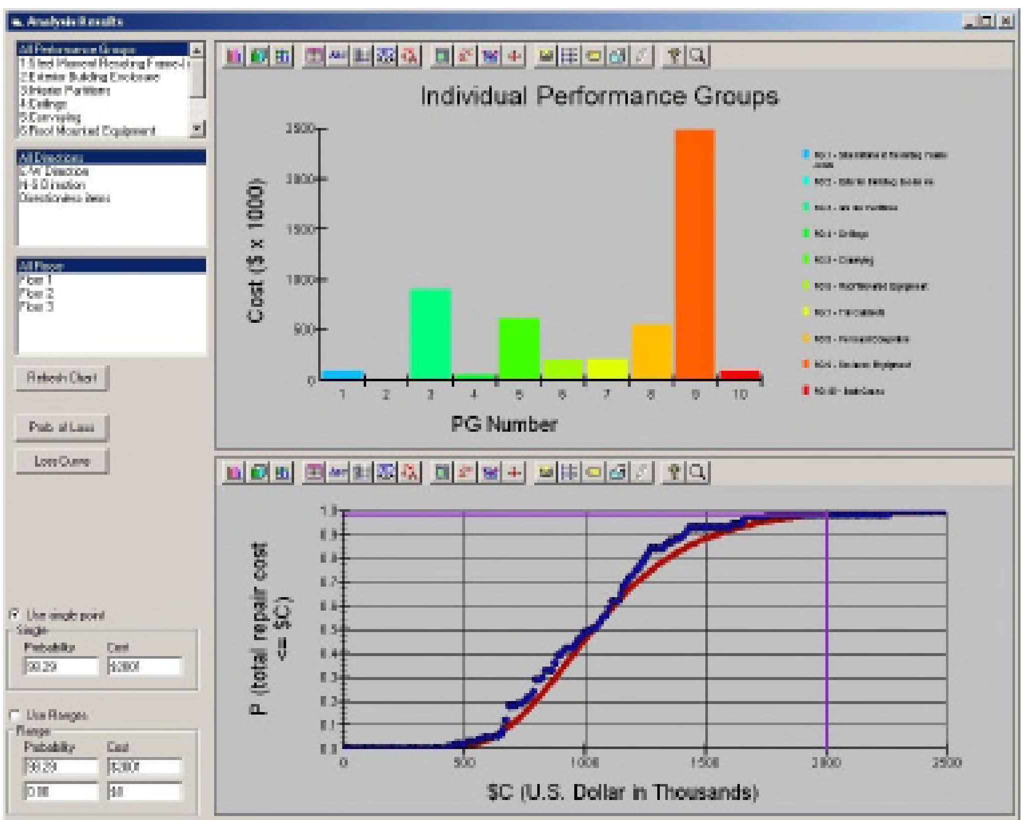


Figure 14. Loss curve for intensity- or scenario-based assessment

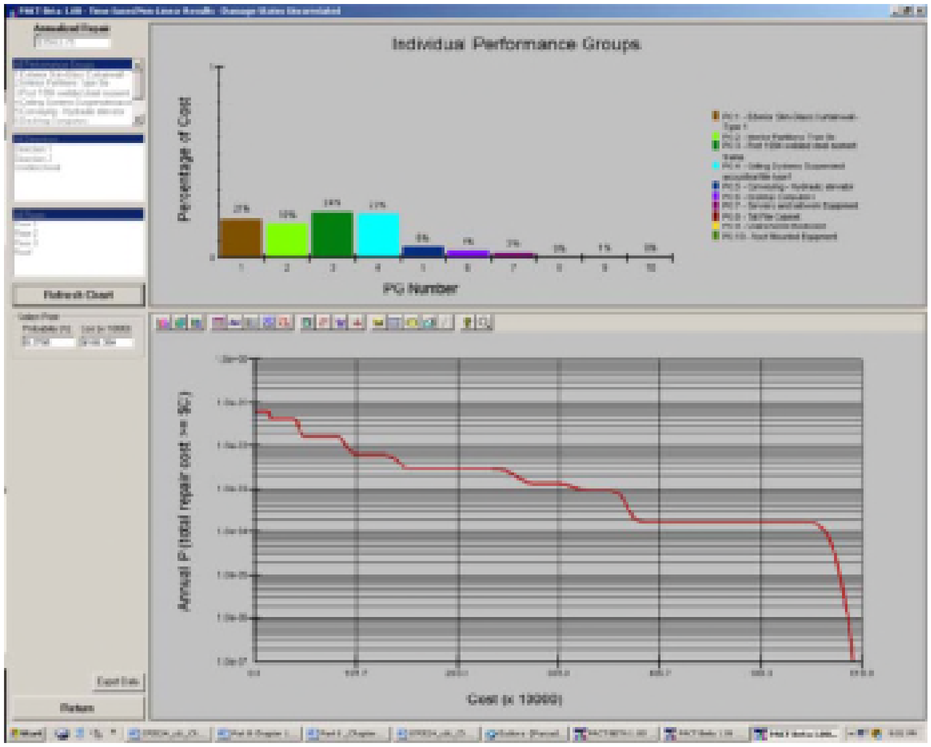


Figure 15. Annualized loss curve

ACKNOWLEDGEMENTS

The development of the *Guidelines* described in this paper for implementing the next-generation procedures for performance-based earthquake engineering is being funded primarily by the Federal Emergency Management Agency (FEMA) of the United States Department of Homeland Security. The Applied Technology Council (ATC) is leading the development effort for FEMA under its ATC-58 project to develop Next-generation Performance-based Seismic Design Criteria.

Numerous individuals made important contributions to the development of the 35% draft *Guidelines* and the procedures presented therein, including, Robert Bachman, Dr. Allin Cornell, Craig Comartin, Dr. Greg Deierlein, Dr. Robert Hanson, Jon Heintz, John Hooper, Michael Mahoney, Andrew Merovich, Dr. Jack Moehle, Maryann Phipps, Christopher Rojahn and Dr. Tony Yang. These contributions are gratefully acknowledged.

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