Ninth Canadian Conference on
Earthquake Engineering
Ottawa, Ontario, Canada
26-29 June 2007

DEVELOPMENT OF NEXT-GENERATION PROCEDURES FOR PERFORMANCE-BASED EARTHQUAKE ENGINEERING

R.O. Hamburger[1]

ABSTRACT

The Applied Technology Council with support from the Federal Emergency Management Agency and cooperation of the three U.S. national earthquake engineering research centers is developing a series of next-generation performance-based earthquake engineering procedures and guidelines. These guidelines employ structural reliability methods to characterize performance in terms of potential earthquake-induced losses resulting from building damage. Losses considered include casualties, repair/replacement costs, and loss of occupancy and use. The procedures are applicable to new and existing buildings. Though formulated specifically for earthquake engineering the basic methodology is equally applicable to design for other hazards including wind, snow, blast and fire.

Introduction

Development of performance-based earthquake engineering in the United States initiated in the late 1980s and early 1990s, following a series of moderate magnitude earthquakes in California that resulted in few casualties but very large economic losses. At the time, the performance goals intended for building code seismic provisions, as described in commentary (SEAOC, 1974) was to avoid damage in minor earthquakes, avoid structural damage in moderate earthquakes and avoid structural collapse in the most severe earthquakes. The estimated $15 billion of economic losses in the1989 Loma Prieta earthquake and $30 billion in the 1994 Northridge earthquake suggested that these performance goals were not adequate. Individual lenders, corporate and institutional building owners and corporate tenants began to insist that buildings be capable of limiting losses in likely earthquake events. In particular, many owners of existing commercial buildings, in response to economic pressures from stakeholders began to request that engineers upgrade buildings to provide acceptable exposure to repair costs, expressed as probable maximum loss. Engineers, unfortunately, did not have consensus standards to respond to these demands,

In the early 1990s, the Federal Emergency Management Agency (FEMA), looking for ways to encourage owners of existing buildings to perform upgrades and reduce future human and economic losses, initiated the development of national seismic rehabilitation guidelines. This effort was executed jointly by the Applied Technology Council, the American Society of Civil Engineers and the Building Seismic Safety Council. The results of this large scale effort were first published as the FEMA-273/274 (ATC, 1997) reports. The Structural Engineering Institute of the American Society of Civil Engineers then converted

---

[1] Senior Principal, Simpson Gumpertz & Heger Inc., The Landmark @ 1 Market, Suite 600, SF, CA

these guidelines into the FEMA-356 (ASCE, 2000) prestandard and most-recently the ASCE-41 Seismic Rehabilitation Standard (ASCE, 2006) and also produced a companion performance-based evaluation standard, ASCE-31 (ASCE, 2002). The procedures contained in this succession of reports comprises the present generation of performance-based seismic analysis and design procedures in the United States.

These present-generation procedures have been widely accepted by the U.S. engineering community. They have been used for hundreds, if not thousands of seismic evaluations, hundreds of seismic retrofits and even for the performance-based design of a number of new buildings including a number of very tall buildings. The State of California has adopted these procedures into the California Building Code (State of California, 2001) and both the National Fire Protection Association (NFPA, 2003) and International Code Council (ICC, 2001) have adopted codes that incorporate these procedures.

Despite the wide acceptance of present-generation procedures, it is generally acknowledged that they incorporate significant limitations. Building performance is communicated by reference to a series of standard performance levels that range from states of negligible damage and impact on safety, occupancy and use to states of near complete damage in which there is extensive risk to life, complete loss of economic value and permanent loss of use and function. Decision-makers including developers, building owners and building officials are expected to specify the particular performance levels that are to be achieved for given levels of earthquake shaking. However, the relationship between these standard performance levels and the actual performance outcomes are at best qualitative, making it difficult for decision-makers to determine appropriate objectives for a building. The simulation procedures used to assess performance rely heavily on static nonlinear analysis, an outdated and inaccurate methodology for many structures. The procedures used to determine acceptability of performance are dominated by the performance capability of individual structural components rather than the building as a whole, often resulting in grossly pessimistic projections of performance capability. Finally, the procedures for assessing the performance of non-structural systems and components, a principal contributor to economic and occupancy losses are not performance-based at all, but rather an extension of present-day procedures for design of new buildings.

As FEMA’s efforts to develop the present-generation procedures, intended to address seismic evaluation and upgrade of existing buildings neared completion, FEMA began to lay the ground work for development of procedures that would address new construction. Both the Earthquake Engineering Research Center (EERC, 1996) and Earthquake Engineering Research Institute (EERI, 2000) developed action plans on behalf of FEMA for development of performance-based engineering criteria for new buildings. Both plans called for massive programs that included basic research in seismology and structural behavior, engineering guidelines and guidelines for decision-makes.

In 2001, the FEMA entered into a contract with the Applied Technology Council to implement, on a limited basis, the FEMA-349 action plan developed by the Earthquake Engineering Research Institute. The program, known as the ATC-58 project is being executed in phases, over a protracted period, and includes no basic research, which is to be conducted separately and cooperatively by the United States Geologic Survey, the three national earthquake engineering research centers and the National Science Foundation sponsored NEES program. Initial goals of the program include development and publication of performance-assessment guidelines that will enable engineers to more reliably assess the probable performance of both new and existing buildings. Following successful completion of this phase, the project will develop criteria and guidelines that can be used to reliably design buildings for target performance capability.

Characterization of Performance

Next-generation procedures will characterize performance in terms of the probability that a building’s response to earthquake shaking will result in casualties, that is, deaths and serious injuries; direct economic loss, that is the cost of repair or replacement of damaged facilities; and occupancy interruption time. These performance measures will be quantified, both in terms of the magnitude of the specific loss, that is number of deaths, dollars or repair cost, days of occupancy interruption, and the probability that such losses will actually occur. These performance measures were selected based on feedback from decision-makers, including owners, tenants, insurers, lenders, and building officials as to the most useful means of expressing performance. The probabilistic approach to expression of performance measures was selected to acknowledge the inherent uncertainty associated with assessing the performance of a building in a future event and also to provide a measure of liability protection for engineers. Under present-generation procedures, performance is expressed as an absolute, creating significant potential liability for design professionals in the event that actual performance is poorer than that selected as a basis for design. The project team felt that the use of probabilistic expressions of performance would make it evident that there was a possibility for adverse performance and thereby relieve somewhat the liability burden on the engineer practicing performance-based design.

Three types of assessments: intensity-based, scenario-based and time-based are possible. Intensity-based assessments permit estimation of probable losses conditioned on the building being subjected to a specific intensity of ground shaking. In these guidelines, earthquake intensity is represented by an elastic, 5%-damped response spectrum. These assessments account for the uncertainties associated with definition and modeling of the building's structural and nonstructural characteristics; prediction of response and damage and prediction of the consequences of damage, that is the losses. Results of intensity-based assessments can include such performance projections as the probability of incurring more than a given number of casualties, the expected days of occupancy interruption or the repair cost that has less than a 10% chance of exceedance, given that the building is subjected to the specific earthquake intensity. Intensity-based assessments are of limited utility by themselves, but are the building block from which other assessment types are developed.

Scenario-based performance assessments are used to assess building performance for a specific earthquake, defined by a location and magnitude. Intensity is taken as a lognormal distribution of 5%-damped response spectra, where the median and dispersion of the spectra at each structural period are based on an appropriate attenuation relationship. In addition to the uncertainties inherent in intensity-based assessments, scenario-based assessments account for the uncertainty associated with prediction of ground motion intensity even if the magnitude and source distance of an event relative to a property are well-defined. The results of scenario-based assessments are expressed in a similar manner to those of intensity-based assessments, except that they are conditioned on the specific earthquakes scenario, rather than a particular shaking intensity. Scenario-based assessments are most useful to decision-makers with property located proximate to a well-defined active fault. For example, decision-makers in San Francisco might be interested in scenario-assessments conditioned on a recurrence of the 1906 earthquake while decision-makers in British Columbia may wish to assess building performance conditioned on the occurrence of a large Cascadia subduction event.

Time-based assessments are used to evaluate the potential losses over a specific period of time considering all earthquakes that could occur in this time period and the probability of occurrence of each. Intensity is represented by mean hazard curves at various structural periods from which uniform hazard spectra at specific annual frequencies of exceedance can be constructed. Time-based assessments incorporate all of the uncertainties inherent in scenario-based assessments as well as the significant uncertainty associated with prediction of the magnitude and locations of future earthquakes. Results of time-based assessments are expressed as mean annual frequencies of exceedance for casualties, direct economic loss and days of occupancy interruption. They are directly useful in performing cost—benefit studies to determine appropriate levels of seismic-resistant design for specific buildings. They are also useful in evaluating the risks inherent with a specific seismic design against other risks including fire and wind.

For each of the assessment types, it is possible to identify, not only the aggregate losses, but also the principle sources of loss. As an example, for a given design it may be found that a large fraction of predicted repair costs are associated with damage to exterior cladding and that this damage is principally the result of large story drift at moderate shaking levels. With this type of information available, efforts to improve the design's performance can focus on selection of a more damage-resistant cladding system, improving the detailing of the cladding system, or modifying the structural system to reduce drift potential. Similarly, other sources of poor performance can be directly identified providing the designer a significant advantage in attempting to meet selected project performance goals.

Performance Assessment Methodology

Figure 1 outlines the five basic steps in the performance assessment process. The process initiates with definition of the building's basic configuration and characteristics including its site location, site conditions, construction, and occupancy. It is never possible to define these characteristics precisely. The total number of persons present in the building at the time an earthquake occurs cannot be defined with certainty, nor can the locations and value of all the furnishings that will be present. It is impossible to know the age and condition of the mechanical equipment and piping at the time the earthquake occurs. Similarly, even when a detailed geotechnical investigation is available it is only possible to estimate the site subsurface conditions. Even the actual strength, stiffness and damping of the structural system can only be estimated. Therefore, to make a meaningful assessment of building performance, it is necessary to develop estimates of the probable value of each of these characteristics that effect performance and to assess plausible variations in these characteristics.

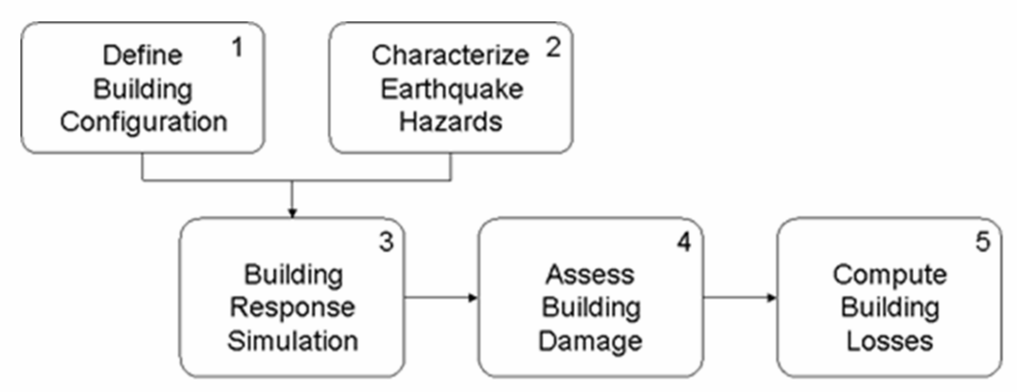


Figure 1. Flow diagram for performance assessment methodology.

A primary input into the performance assessment process is the definition of the earthquake hazards, that is, 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 landsliding. 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. At the present, the performance-assessment guidelines address only shaking hazards though the methodology could be expanded to address other earthquake hazards such as liquefaction and lateral spreading. As discussed in the prior section, intensity is represented by 5% damped elastic response spectra, measures of the dispersion of these spectra for specific scenarios and measures of the annual frequencies of exceedance of these spectra for time-based assessment.

Following definition of the building characteristics and seismic hazard, the next step in the performance assessment process is to predict the building's response to the hazards. To do this, it is necessary to develop an analytical model of the structure and key nonstructural systems and components and then use this model to analyze (simulate) the effect of the earthquake hazards on the building. The results of these analyses are predictions of demand parameters including building and story drifts, floor accelerations, member forces and deformations. Since it is impossible to define precisely the building's characteristics and the intensity of earthquake effects, it is also impossible to define precisely the values of these demand parameters. Instead, it is necessary to predict a statistical distribution of the likely values of these demand parameters.

Next, the building and story drift, floor acceleration, and other demand data from the structural analyses is used together with data on the building configuration to calculate the possible distribution of damage to structural and nonstructural building components. The prediction of damage sustained by a building component is also quite uncertain, even if the demand on the component is well defined. For example, the prediction of damage sustained by a window, mounted in an exterior wall system may most closely correlate with lateral drift in the story in which the window is mounted. However, the amount of drift that will cause the window to break is dependent on a number of factors including: the way the gaskets are installed in the frame around the window; the manner in which the window frame is mounted in the wall; the way the wall is attached to the structure; and the amount the window moves out-of-plane at the same time it moves in-plane. Like the other factors that affect building performance, it is impossible to predict these factors precisely. Therefore, probabilistic functions, termed fragility functions, that relate the probability that a component will be damaged, to the value of the demand parameter are used to predict damage. Figure 2 is a representative fragility functions for a building component, plotted in the form of a lognormal distribution, characterized by median value, θ and dispersion β.

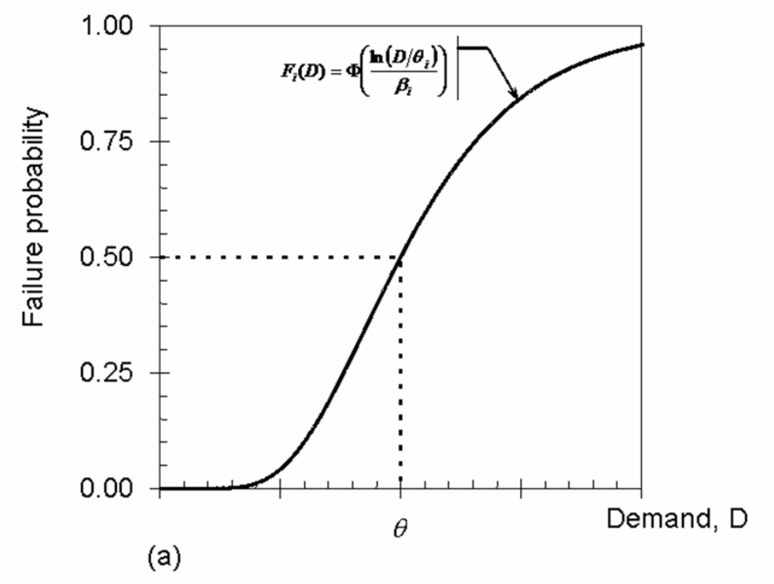


Figure 2. Representative fragility curve relating probability of damage to demand.

A building damage state is a definitive listing of the types of damage sustained by each of the components that comprise the building. Since there is great uncertainty associated with estimating the damage sustained by each component, the building damage state is also quite uncertain. However, it is necessary to estimate a building damage state to assess the performance outcomes. This is also quite uncertain. For example, even in the real case when damage has actually occurred, different contractors will typically charge different amounts to repair the damage, depending on their own individual cost structures, how busy each one is, and the skill of their individual workers, the amount of profit they wish to make and how careful they are in estimating the project. Similarly, the amount of time that a damaged structure will be unoccupied will depend not only on the extent of damage but also on the efficiency of the owner in retaining a contractor to make repairs, the efficiency of the contractor, the availability of materials and labor and other factors that are impossible to predict with certainty. The casualties that may occur if a building collapses will depend on how many people are actually in the building at the time of the earthquake, where they are in the building, and even how they react as the building starts to fail. As with other steps in the performance assessment process, it is only possible to form statistical estimates of these factors rather than to determine them precisely.

Since each of the steps in the performance assessment process is inherently uncertain, performance is expressed in a probabilistic manner in the form of a central value, or “best-estimate” of the probable losses together with a measure of the possible variation of the actual losses in a specific earthquake from this central value. There are several ways to derive these probabilistic distributions of performance. One way is to develop mathematical functions that represent the probability of occurrence of each of the key factors that affect performance including earthquake intensity, structural response, damage and consequence, and then to mathematically integrate or convolve these various functions to from the damage probability. The Pacific Earthquake Engineering Research Center (PEER) developed such a methodology (Deierlein, 2004) which underpins the procedures and tools used in the ATC-58 project. This methodology involves solution of the so-called framework equation:

$$v\left(DV\right)=\iiint G\left\langle DV\middle|DM\right\rangle \mid dG\left\langle DM\middle|DP\right\rangle \mid dG\left\langle DP\middle|IM\right\rangle \mid d\lambda(IM) \qquad (1)$$

Where, $v(DV)$ is the annual frequency of exceedance of a given loss, called a decision variable by PEER; $G(DV|DM)$ is the conditional probability of incurring a given loss as a function of a damage state or damage measure; $dG(DM\{DP)$ is the conditional probability of being damaged to a given state, given a structural response state; $dG(DP|IM)$ is the conditional probability of experiencing a given response state, given an intensity of earthquake shaking and $d\lambda(IM)$ is the incremental probability of incurring ground shaking of intensity *IM*.

Closed form solution of the PEER framework equation requires the development of mathematical expressions for each term in equation (1). While this can be done for simple systems, it is not feasible to develop such nonlinear expressions for all types and sizes of building. Consequently, the ATC-58 project uses Monte Carlo type procedures to make these calculations. For each of a series of intensities, the engineer selects and scales a suite of ground motions to the spectrum that represents the intensity and performs a series of response history analyses to obtain a distribution of story drifts and floor accelerations at the intensity. From this limited suite of analyses a joint probability distribution of story drifts and accelerations is formed. Then, using random selection techniques a series of several hundred building response states are generated from this joint probability distribution.

For each building response state, termed a realization, damage states are assigned to each of the building's structural and nonstructural components. These response states are assigned using fragility functions, such as that of figure 2, where the probability of damage is taken as a function of a single demand parameter such as story drift in a particular direction or floor acceleration. Fragility functions can be developed using laboratory test data, observation of actual earthquake damage, expert judgment or a combination of these. The ATC 58 project has published a companion guideline (ATC, 2006) for developing fragility data in cooperation with the three national earthquake engineering research centers. Development of typical structural and nonstructural fragility functions is a major task of the AT-58 project.

Once damage states are assigned to the building components for a realization, the consequences of the damage are computed using consequence functions. Consequence functions are lognormal distributions of the probability of incurring casualties, direct economic loss and occupancy interruption as a direct function of the damage states. Development of these consequence functions is also a major task of the ATC-58 project. The distribution of losses obtained from the several hundred realizations defines the desired assessment results which is the probability of incurring losses of various types for the given building design. For intensity-based assessments this process is performed for a single intensity. For scenario-based assessments the process is performed for a series of intensities, each having equal probability of occurrence, given the scenario earthquake. For time-based assessments a series of intensities, the probably of each taken in accordance with the hazard curve are used. The probability of incurring losses are then factored by the probability of experiencing the intensity of motion to obtain the final performance projections.

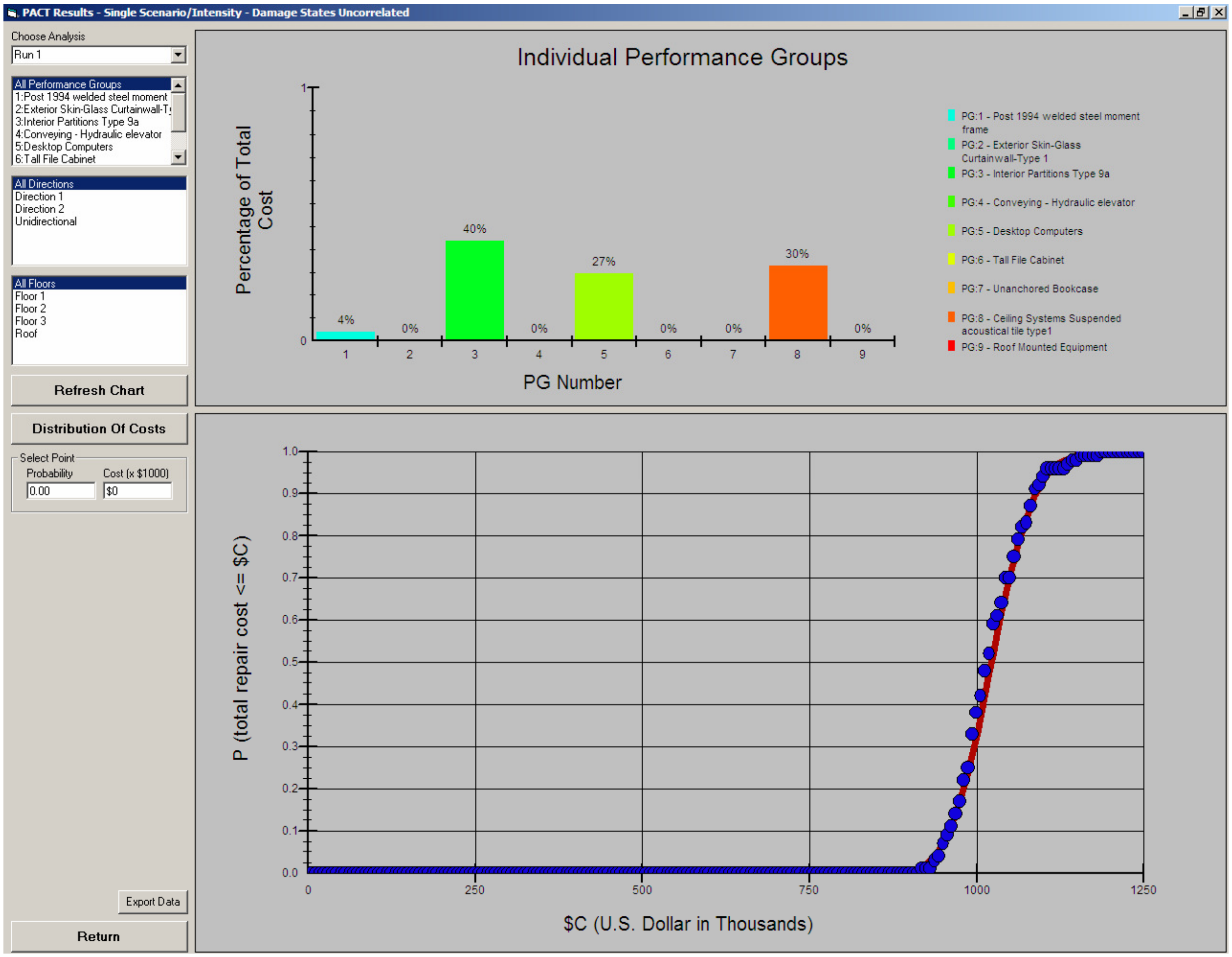
Performance Assessment Calculation

The performance assessment calculation process described in the previous section is both mathematically complex and unfamiliar to the practicing structural engineer, who is the target user for the guidelines and procedures produced by the project. Therefore, the performance assessment guidelines produced by the ATC-58 project will include a software package, termed the Performance Assessment Calculation Tool or PACT. PACT will both perform the complex mathematical manipulations described in the previous section and also serve as a repository for default database of fragility and consequence functions for common structural systems and nonstructural features contained in common building occupancies.

Engineers using the performance assessment process will have several options. For buildings employing common structural systems and occupancies, a simple form of assessment is available. In simplified assessment, the engineer need only define basic building data including the building occupancy type, for example, commercial office, residential, etc.; the number of stories; and the floor area at each level, together with building response data. From this basic data, PACT computes the quantity of various building components present in the building, which the engineer can review and modify as appropriate. Building response data, which include drift and acceleration data in each of two orthogonal directions at each intensity level of interest is obtained by performing simplified linear analyses to which default correction coefficients and dispersion values are assigned within PACT. From this basic data, PACT develops the joint probability distributions of structural response at the various intensities, develops realizations and calculates the distribution of losses, as described above.

Output from PACT includes information on the probability of exceeding losses of various levels, for the building as a whole, for individual stories, or even by individual types of components, such as exterior cladding, plumbing fixtures, etc, termed performance groups. This data will allow an engineer performing a design to evaluate the principal sources of loss and assess the sensitivity of the loss predictions to various design decisions. Figure 3 is a typical output screen from PACT. Shown at the bottom of this screen is a plot of the cumulative probability of non-excedance for various repair costs for either a particular intensity of ground shaking or a particular earthquake scenario. Also shown are the contribution to the total building loss of components in different performance groups.

Using PACT, structural engineers will be able to perform basic assessments with limited effort and using procedures that are familiar to them today. However, because the definition of a building's construction used in basic assessment is imprecise as is the analysis used to predict response, it is expected that the results of basic assessment will inherently include very large uncertainty. Engineers who desire reduced uncertainty in their performance assessments can obtain this by using enhanced assessment options embedded within the guidelines. These enhanced assessment options include: use of nonlinear response history analysis to define building response; more detailed definition of building contents; and user-defined fragility and consequence functions.



Choose Analysis: Run 1

Probability: 0.00

Cost (x $1000): $0

Figure 3. Representative PACT output.

Project Status

Presently, the project has developed a 35% draft of the performance assessment guidelines together with a preliminary working release of the PACT software. This version of PACT accommodates assessment of direct economic losses for light wood frame structures and moment-resisting steel frame structures of either residential or commercial office occupancy. Over the course of the next four years, the project will focus on expanding the methodology to include casualties and occupancy interruption losses and also expand the default databases to include additional occupancies and structural system types. Additional occupancies will include education, healthcare, retail, hospitality, and warehouse. Default structural data will be developed for most structural systems commonly constructed in the United States in the past 50 years.

Once the assessment guidelines and PACT are published, the project will focus on the development of guidelines for design of buildings to achieve desired performance. A major part of this second phase will include the use of the assessment procedures to assess typical buildings constructed to present day building code requirements in order to better quantify the performance embedded within the present building codes. This will serve as the basis for forming recommended performance objectives for new structures of different occupancies.

Following quantification of performance objectives, the project will use the assessment procedures to determine the relationship between structural strength, stiffness, damping, ductility, and methods of installing nonstructural components and systems on the performance capability of buildings in different seismic environments. This data will be used to formulate recommendations that will enable to use conventional design approaches to achieve designs with specific performance capability.

Conclusions

The concept of performance-based seismic design initiated in the United States in the 1980s in response to large economic losses that were incurred in relatively moderate earthquakes. In the 1990s, FEMA sponsored the development of a first generation of performance-based design procedures and guidelines that have received great acceptance in the design community and are routinely used in the U.S. to evaluate and retrofit existing buildings. These first generation procedures are also seeing increasing use in the design of new buildings. However, the first generation procedures do not provide a means of characterizing performance that is sufficiently useful to those decision-makers who must decide the performance capability that a given building should be designed to achieve. Also, the first generation procedures use now out-dated procedures of questionable reliability.

Presently, the Applied Technology Council is engaged in the development of next-generation procedures for performance-based seismic assessment and design of buildings. These next-generation procedures will characterize performance in ways that are directly useful to decision makers and will explicitly indicate the probability that performance may be better than or worse than that selected as a design basis for a given project. Though the procedures employ methods of structural reliability analysis that are not familiar to many engineers, most structural engineers should be able to use the new procedures without obtaining in-depth understanding of these methods. Rather, engineers using the new procedures must be able to define the contents and characteristics of their structures and perform seismic analysis to predict the amount of response the structure will incur at various intensities of earthquake shaking. These data will be manipulated and convolved with default fragility and loss functions to produce assessments of the performance capability of individual building designs in ways that are useful to obtaining optimal designs.

In order to be successful, the ATC-58 project will need to compile a great deal of data on the fragility of various structural and nonstructural systems and components. Standards protocols and procedures for developing these fragility data have been published by the project. Researchers and engineers around the world are invited to participate in the development and compilation of this fragility data.

References

American Society of Civil Engineers, 2000. *Prestandard for Seismic Rehabilitation, Report No. FEMA-356*, Federal Emergency Management Agency, Washington, D.C.

American Society of Civil Engineers, 2002. *Seismic Evaluation Standards, ASCE-31*, American Society of Civil Engineers, Reston, VA

American Society of Civil Engineers, 2006. *Standard for Seismic Rehabilitation, ASCE-41*, American Society of Civil Engineers, Reston, VA

Applied Technology Council, 1997. *Guidelines and Commentary for Seismic Rehabilitation, Report No. FEMA-273 & FEMA-273*, Federal Emergency Management Agency, Washington, D.C.

Applied Technology Council, 2007. *Protocols for Laboratory Testing of Components for Fragility Determination, FEMA-471*, Federal Emergency Management Agency, Washington, D.C.

Deierlein, G.G., 2004. “Overview of a comprehensive framework for Earthquake Performance Assessment”, *Performance-based Seismic Design Concepts and Implementation Proceedings of the International Workshop*, Bled, Slovenia, June 28-July 1, 2004

Earthquake Engineering Research Institute, 2000. *Action Plan for Performance-based Seismic Design, Report No. FEMA 349*, Federal Emergency Management Agency, Washington, D.C.

Earthquake Engineering Research Center, 1996. *Performance-based Seismic Design of Buildings, Report No. FEMA 283*, Federal Emergency Management Agency, Washington, D.C.

International Code Council, 2001. *International Performance Code*, ICC, Whittier, CA

National Fire Protection Association, 2003. *NFPA 5000 Building and Safety Code*, NFPA, Qunicy, MA

State of California, 2001. *California Building Code*, International Code Council, Whittier, Ca.

Structural Engineers Association of California, Seismology Committee, 1974. *Recommended Lateral Force Requirements and Commentary*, Sacramento, California