FEMA P58: Next-Generation Building Seismic Performance Assessment Methodology

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SUMMARY
The Applied Technology Council (ATC) has completed a 10-year program under contract with the Federal Emergency Management Agency (FEMA) for the development of the FEMA P-58 Next-generation Building Seismic Performance Assessment Methodology. Based on the framework for performance-based seismic engineering developed by the Pacific Earthquake Engineering Research Center, the methodology is intended for use in a performance-based seismic design process. Applicable to the assessment of new or existing buildings, the methodology provides engineers the ability to assess the consequences of an individual building's response to future earthquakes. Consequences are expressed as probability distributions for casualties, repair costs, repair time, and posting of unsafe placards. Assessments can be conducted for shaking of a specified intensity; a specified earthquake scenario (i.e., magnitude-distance pair); or considering all earthquakes that may occur over a specified interval of time along with the probability of their occurrence.

Keywords: performance assessment, performance-based design, loss assessment methodology

1. INTRODUCTION

Performance-based seismic design, that is, the practice of designing buildings and other structures with the expectation that they will provide particular desired performance when subjected to earthquakes, has been under development in the United States since the early 1970s. Development initiated following the 1971 San Fernando earthquake, when collapse and severe damage to several hospitals caused engineers to recognize that some buildings are more important than others and should be expected to perform better. The first attempted U.S. codification of performance-based seismic design procedures appeared in the *1976 Uniform Building Code* (ICBO, 1976), with the introduction of Occupancy Importance factors to the calculation of design seismic forces with the intent and belief that increased seismic forces would produce enhanced robustness and improved performance. Though this approach to performance-based design remains embedded in U.S. building codes today, engineers soon came to realize that enhanced strength alone was not sufficient to reliably provide enhanced performance. Over the years, other features were added to the building codes including requirements for construction quality assurance, control on system regularity, limitation on permissible structural systems, increasingly prescriptive detailing requirements, and criteria to anchor and brace non-structural components, all with the intent of enhancing building performance.

Yet an essential feature of performance-based design—quantitative identification of the performance desired and identification of the severity of seismic hazards for which it is to be obtained—remained absent from the codes until the publication of ASCE/SEI 7-10 (ASCE, 2010). For the first time, the ASCE/SEI 7-10 standard placed quantification of the intended risk of failure for structures of various occupancies into its commentary. Even this recent publication quantitatively addresses only those risks associated with structural failure and collapse, not risks associated with loss of serviceability or function, key considerations in the earthquake performance of buildings and structures.

In the mid-1980s, following a series of frequent, but moderate magnitude California earthquakes that caused extensive economic loss, the United State became interested in reducing the seismic risk associated with its existing building stock, much of which had been designed to outdated and unreliable building code requirements. Government agencies, corporations and individual building owners asked engineers to assess their buildings and evaluate the likely performance of these structures in future earthquakes. The only tools available to assist engineers at that time were the building codes and the engineers' individual judgments, which engineers quickly realized were not up to the task. FEMA, charged with advancing the nation's earthquake preparedness and mitigating future losses under the National Earthquake Hazards Reduction Program (NEHRP) began to fund a series of projects aimed at providing engineers with more reliable tools to predict an existing building's likely earthquake performance and to enable seismic upgrade design to achieve desired performance. These efforts culminated in 1997 with the publication of the FEMA-273/274 (FEMA, 1997) seismic rehabilitation guidelines, later revised as the FEMA 356 pre-standard and then re-published by the American Society of Civil Engineers as their ASCE/SEI 41-06 standard.

The ASCE/SEI 41-06 standard defines the present generation and current state of performance-based seismic design in the United States today. It includes embodiment of the basic performance-based design process (Figure 1) that initiates with a formal statement of quantitative performance objectives, development of preliminary design and then evaluation to determine if the design is capable of achieving the targeted performance objectives. Performance objectives are framed as statements of desired performance, quantified by several standard performance levels: Immediate Occupancy, Life Safety and Collapse Prevention, coupled with definition of the seismic hazard level for which this performance is to be achieved. Performance assessment is performed by: 1) constructing an analytical model of the building structure; 2) analyzing the model using a design ground motion to predict the values of key response quantities, typically, element forces and deformations; and 3) comparison of these response quantities with tables of acceptable values keyed to structural component type, detailing, and performance level.

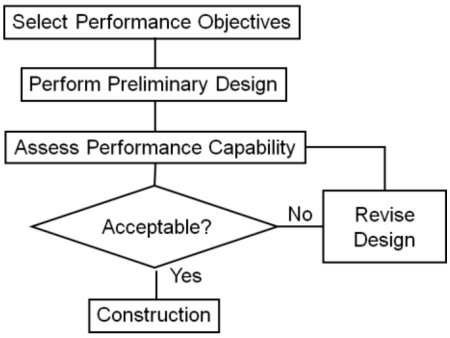

Figure 1. Performance-based seismic design process

The U.S. engineering community rapidly embraced the FEMA 273/274 guidelines and its successor documents and applied them not only to evaluation and rehabilitation of existing buildings, their intended purpose, but also to the design of major new buildings, including some very tall structures. Despite the eagerness with which engineers adopted these procedures, engineers also recognized that enhancements were needed. First, these present generation procedures did not treat the performance of non-structural components in a performance-based manner, relying instead on the provision of adequate bracing, anchorage, and deformation capacity to assure performance. In addition, the procedures are element-, rather than system-based, with structural performance based on the demands and capacities of individual structural components. Finally, and perhaps most significantly, the reliability inherent in the procedures is undefined. While some engineers believe the present generation procedures are conservative, and will generally result in buildings with better performance capability than targeted, others fear the substantial liability associated with designing a building for specific performance, then having the building fail to achieve this performance when subjected to an earthquake.

Even as the FEMA 273/274 guidelines neared completion, FEMA began planning development of next-generation guidelines to address the above concerns and also extend the rehabilitation guidelines to new building design. FEMA commissioned two separate efforts to develop program plans for development of next-generation guidelines; one prepared by the Earthquake Engineering Research Center (EERC), University of California at Berkley, and published as FEMA 283 (EERC, 1996) and one prepared by the Earthquake Engineering Research Institute (EERI) and published as FEMA 349 (EERI, 2000). Both documents called for broad programs of research and development including extensive laboratory testing of structural and non-structural components to quantify their performance capability; improvement of analytical simulation methods to enable more reliable performance prediction; broad socio-economic studies to determine appropriate performance criteria for buildings of different types; and information dissemination efforts to train engineers and stakeholders in how to take advantage of the new tools.

Funding required for the broad programs proposed by EERC and EERI was not forthcoming; however, in 2001, FEMA funded the Applied Technology Council (ATC) to initiate development of next-generation performance-based design criteria with an initial task to develop tools to enable engineers to reliably predict the earthquake performance of new and existing. After 10 years, the resulting FEMA P-58 (FEMA, 2012) publication and its companion products are complete.

2. BASIS

The project initiated in 2002 with a series of workshops to obtain stakeholder input on needed improvements to the newly developed practice of performance-based seismic design. The first workshop included practicing structural engineers from seismically active regions of the United States together with prominent earthquake engineering researchers. This technical group pointed out the need to define and improve the reliability of performance-based engineering approaches and extend them to more appropriately include non-structural element behaviour. A second workshop included a broader group of stakeholders and decision makers including commercial real estate investors, insurers, lenders, attorneys and architects. This second group provided direction that the standard performance levels contained in present-generation procedures were not useful to decision-makers because they are not quantitatively tied to the performance measures needed to make investment decisions including probable life, financial and occupancy losses. These decision-makers also admonished the development team to be honest about the certainty, or lack thereof, associated with quantification of probable performance. With this input in hand, the project team looked to the performance-based seismic engineering framework (Moehle and Deierlein, 2003), then under development by the Pacific Earthquake Engineering Research Center (PEER).

The PEER framework expresses earthquake performance in terms of the probable values of key performance measures, such as casualties, repair costs, and occupancy loss derived from an application of the total probability theorem. Specifically, the probable value of an earthquake loss measure is obtained from Equation 2.1

$$Performance = \iiint \{PM|DS\}\{DS|EDP\}\{EDP|I\}dz \tag{2.1}$$

where, *PM* is the value of a performance measure, e.g., repair cost, given the occurrence of a particular damage state, *DS*; *EDP*, engineering demand parameter, is the value of a response quantity such as element plastic rotation demand, given an intensity of ground motion, *I*, and the integration occurs over the range of seismic hazards, considering uncertainty in hazard, response, damage and consequence.

The PEER framework requires definition of each of the key variables in a manner that permits integration in the form of Eq. 2.1. Closed form solution of this equation is difficult, even for simple structural systems with limited damage states, and is problematic for systems as complex as real buildings. Yang et al. (2006) developed an application of this framework that utilized a modified Monte Carlo approach to implement the integration using inferred statistical distributions of building response obtained from limited suites of analyses. The ATC project team ultimately adopted and expanded this approach into the FEMA P-58 methodology.

3. METHODOLOGY

The FEMA P-58 methodology expresses performance as statistical distributions of the probable values of key earthquake impacts in a form similar to that shown in Figure 2, termed a performance function. Key earthquake impacts addressed include repair costs, repair time, serious injuries requiring hospitalization, and deaths. The methodology also projects the probability of incurring unsafe placards by post-earthquake building inspectors. Work is currently underway to provide capability to address additional impacts including CO_2 emissions, energy utilization and solid land fill generation associated with repair of earthquake damage.

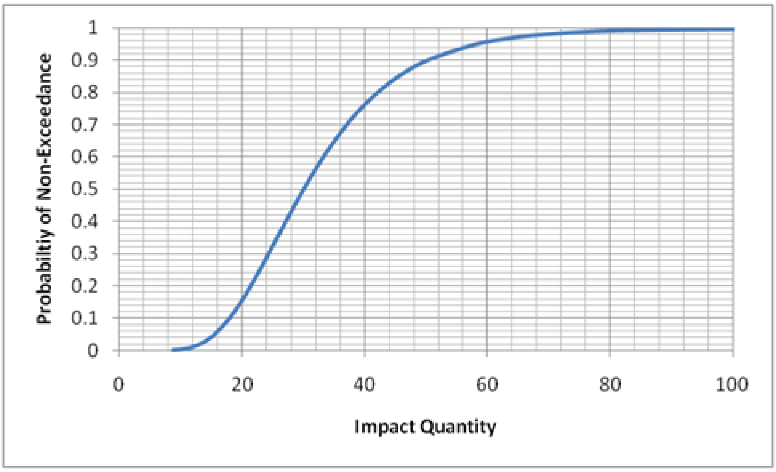

Figure 2. Typical performance function

The methodology enables three different types of performance assessments. Intensity-based assessments enable development of performance functions conditioned on the occurrence of a particular ground shaking intensity, such as that represented by an elastic, 5%-damped, acceleration response spectrum. Scenario-based assessments provide performance functions conditioned on the occurrence of a particular earthquake scenario defined by an event magnitude and distance from the building site, taking into account uncertainty in ground shaking intensity, given a defined event. Time-based assessments produce performance functions considering all possible earthquake scenarios and the annual frequency of exceedance of each scenario, taking into account event uncertainty. Figure 3 illustrates the FEMA P-58 assessment process.

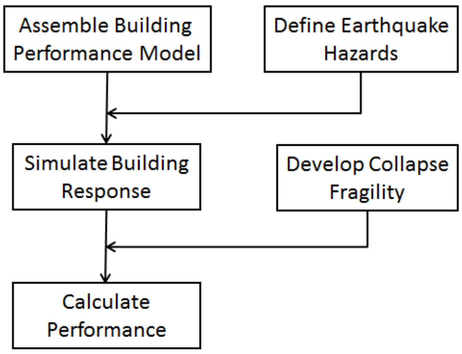

Figure 3. FEMA P-58 performance assessment process.

3.1 Building Performance Models

The process initiates with assembly of a building performance model. The performance model is an inventory of the building assets at risk of shaking-induced damage, including structural and non-structural components, and a building population model. Components are classified by fragility groups and performance groups. A fragility group consists of all those similar components (e.g., suspended light fixtures) that have similar vulnerability to shaking-induced damage, and similar consequences of damage. Each fragility group is categorized using a system based on the NIST Uniformat II system (NIST, 1999) and contains: a description of the component; a description of possible damage states; identification of the demand parameter that best predicts damage onset; a median value of the response parameter at which each damage state is likely to occur; dispersion representing uncertainty in the onset of damage as a function of demand; logical relationships between the several damage states; and, consequence functions that describe a distribution of possible losses given the onset of damage. Although damage occurs in an infinite spectrum of possible states, in the FEMA P-58 methodology damage states are selected as discrete states representing unique consequences associated with repair procedures, life loss, or post-earthquake occupancy consequences. For example, one damage state for concrete walls encompasses all sizes and severity of cracks that are repaired by epoxy injection. A second state encompasses cracking and spalling of the wall requiring recasting of portions of the wall in addition to epoxy injection. A third identifies this damage together with yielding and buckling of reinforcement, requiring wall replacement.

Consequence functions are also statistical distributions accounting for uncertainty in pricing and efficiency, and are adjustable to account for quantity of repair required and difficulty of repair based on such factors as building occupancy and height. A performance group is simply that subset of fragility group members that will be subjected to the same demand, e.g., light fixtures at the third story.

The FEMA P-58 report provides complete data for more than 700 fragility groups including a variety of structural and non-structural components. The fragility group library includes structural systems of concrete, masonry, steel and wood; building cladding and glazing systems; elevators; and mechanical, electrical and plumbing systems. Different fragility specifications are provided considering the level of seismic detailing provided. Thus, fragility specifications are available for structural elements ranging from those with modern ductile detailing to ordinary systems not specifically detailed for seismic resistance. Typically, these fragility groups use either peak floor acceleration or peak story drift as the demand parameter used to determine damage. Sliding and overturning of unanchored components is determined using peak floor velocity as the predictive demand. Users can identify other demand parameters, such as element plastic rotation or strength demand, if needed.

Building population models are used to determine casualties. They are descriptions of the number of people present per 1,000 square feet of building floor space during different times of day and different days of the week. The FEMA P-58 report provides representative population models for eight common occupancies including education, healthcare, hospitality, office, research, residential, retail, and warehouse. Users can assign different occupancies to different building areas or create their own population models independent of those provided.

3.2 Response Simulation

Structural analysis is used to project the probable statistical distribution of response parameter values, given an intensity of shaking. The methodology permits two analytical procedures. The preferred analysis method consists of nonlinear dynamic analysis, using multiple suites of ground motions scaled to represent the target intensity of shaking, or the scenario event. From the suites of analyses, a median value of key response parameters is extracted together with record-to-record variability, and a correlation matrix that together with the record-to-record variability, augmented to include additional modelling uncertainty is assumed to be representative of a joint lognormal distribution of demand.

An alternative simplified analytical method is available for low- and mid-rise structures with moderate inelastic demands. This method uses an elastic equivalent lateral force technique similar to that contained in ASCE/SEI 41-06. Using analyses of representative structural models, Huang and Whittaker (2008) developed statistical correlation functions to derive median estimates of peak floor acceleration, story drift, and floor velocity from this simplified analysis using the predicted drifts, peak ground acceleration, peak ground velocity and estimates of the structure's yield strength. These median demand estimates are coupled with judgmentally selected dispersions to provide distributions of probable demands.

Residual drift is an important parameter for loss determination. The simplified analytical method is not capable of predicting this parameter. Although nonlinear response history analysis can predict residual drift, such predictions are highly unreliable given typical models employed by engineers today. Consequently, based on internal project study (Deirelein 2010) the methodology recommends determination of residual drift as a fraction of peak transient drift, considering the amount of inelastic response, as measured by the ratio of the peak transient drift to yield drift.

3.3 Earthquake Hazards

At this time, the FEMA P-58 methodology is limited to consideration of earthquake shaking hazards only, though it could be expanded to include consideration of other hazards including liquefaction and permanent ground deformation. The manner in which shaking hazards are characterized depends on the type of assessment to be performed and the analytical method that will be used to simulate response. For intensity-based assessments users must select an elastic acceleration response spectrum that represents the intensity of interest. If simplified analysis is to be used, the spectral response acceleration at the structure's fundamental response mode in each of two orthogonal directions is determined and used as input to the analysis. If nonlinear response history analysis is to be used, the user must select and scale suites of ground motion pairs for use in the analysis. The pairs are amplitude scaled so that in average, they envelope the target spectrum. If the spectral shape of the selected records matches the target spectrum well, as few as seven pairs of motions can be used. If the spectral shape of the selected records does not match the target well, 11 or more pairs are recommended.

For scenario-based assessments, users must employ a ground motion prediction model to determine a median acceleration response spectrum for the magnitude-distance pair. For simplified analysis, spectral accelerations are extracted from this median spectrum at the structure's fundamental periods. For response history analysis, suites of ground motions are selected and scaled as described above for intensity-based assessment. The dispersion associate with the ground motion prediction equation is incorporated into response statistics to account for uncertainty in motion given the scenario.

For time-based assessment, it is necessary to determine a spectral response acceleration seismic hazard curve for the building site at the building's effective fundamental period, taken as the average of the structure's fundamental period in each of two orthogonal response directions. Users divide the hazard curve into eight segments ranging from a spectral acceleration at which little damage is likely to occur, to a spectral acceleration associated with frequencies that are unlikely to significantly affect the aggregate loss, recommended as an annual frequency of 0.0002. A central value of spectral acceleration in each hazard segment is selected and an intensity-based assessment is performed at each of these intensities. The time-based assessment is constructed by numerically integrating the results of these eight individual intensity-based assessments, weighted by the annual frequency of occurrence of the hazard interval the intensity represents.

3.4 Collapse Fragility

Although the methodology computes casualties related to component damage associated with falling hazards, most earthquake casualties occur as a result of partial or total building collapse. Therefore, it is necessary for users to define a collapse fragility function. Collapse fragility functions indicate the probability of incurring partial or total building collapse as a function of spectral response acceleration at the building's fundamental response period. Like individual component fragilities these are assumed to take the form of lognormal distributions defined by a median value and dispersion.

Users can determine collapse fragility using incremental dynamic analysis (FEMA, 2009) however, this is a time consuming technique. As an alternative, users can infer collapse fragility on the basis of the number of collapses obtained in limited suites of analyses at several intensity levels. Users can also employ a methodology developed by Vamvatsikos and Cornell (2006) that matches collapse fragilities to pushover curves produced by nonlinear static analysis, based on thousands of representative analyses. It is also possible to establish collapse fragility using engineering judgment.

Regardless of how collapse fragility parameters are developed, users must also identify the unique collapse modes that can occur and the probability of each mode's occurrence, given collapse initiation. Each collapse mode is defined by the percentage of total floor area at each level that is subject to space compression by debris from upper levels. Although the results of analysis can be used to assist engineers in determining collapse modes, our present ability to simulate collapse is limited. Therefore, users must typically rely on judgment to establish collapse modes.

3.5 Performance Calculation

A Monte Carlo process is used to determine the possible distributions of losses. Using the median response values and dispersions obtained from structural analysis enriched to consider modelling dispersion and scenario uncertainty, demands are assembled into a median value matrix and correlation matrix that together with the dispersions are used to generate thousands of simulated response states. Each response state is associated with one "realization" where the realization represents one possible outcome of the building's earthquake response to an intensity or scenario shaking event. The process shown in Figure 4 is followed to calculate losses for each realization.

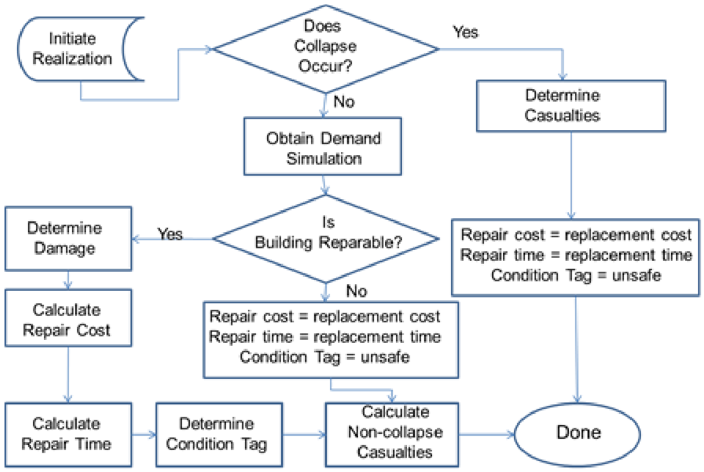

Figure 4. Performance calculation process

Each realization is initiated with assessment of whether collapse occurs or not. This is performed by querying the collapse fragility function with a random integer ranging from 1 to 100. If, at the intensity associated with the realization, the probability of collapse obtained from the collapse fragility is greater than or equal to the random integer, collapse is assumed to occur. If collapse occurs, the collapse mode is determined, again using a random integer and the conditional probability of occurrence of each collapse mode. Next, a random number is used to determine day of the week and hour of day at which collapse has occurred. This information is used to determine the number of people present in the collapsed building area. Together with user-supplied information on the probability of deaths and serious injuries for people in the collapsed building area, the number of casualties is generated. Repair costs and repair time are taken as the building replacement values, regardless of the collapse mode determined.

If collapse is not predicted, then it is necessary to determine the damage state for each of the vulnerable components in the building. This is determined on a performance group basis. When developing the building performance model, users can identify that damage to performance group members is either correlated or uncorrelated. If correlated, all components within a performance group will experience identical damage. Designation of performance groups as correlated speeds damage computation time, but somewhat reduces potential uncertainty in performance outcomes. For correlated performance groups, the methodology uses random numbers and the performance group fragility function to determine which damage state has occurred. For uncorrelated groups this step is performed for each component. This is repeated until a damage state for each vulnerable component in the building has been determined. Then, using the consequence functions, and additional random number generation, the consequence associated with this damage, including repair costs, repair time, post-earthquake unsafe placarding, casualties, etc. are determined. This is summed over all performance groups.

Finally, a determination is made as to whether residual drift is such that the building would be deemed irreparable. To do this, a residual drift fragility having a median value of 1% permanent story drift and a dispersion of 0.4 is recommended. This fragility results in negligible risk of building condemnation at residual drift less than 0.5% and near certain condemnation at residual drift of 2%. Users can alter these values. Residual drift associated with the simulated demand set is compared with the residual drift fragility to determine the probability that the building will be deemed irreparable, and then a random number is used to determine reparability. If the building is deemed irreparable, then the repair costs and times are taken as the replacement values.

The process described above is repeated thousands of times. Then for each consequence (e.g. repair cost) the realizations are assembled in order of magnitude of consequence, from least to greatest. The performance functions are derived as plots of the consequence for these realizations against the percent of realizations having worse consequences.

4. PROJECT PRODUCTS

The FEMA P-58 methodology is published as a package of products that include 1) a report describing the methodology in detail; 2) an implementation guide, describing how the methodology can be used to assess the performance of individual buildings, illustrated with examples; 3) an electronic database of fragility specifications for typical structural and non-structural building components; 4) a spread sheet tool that enable users to determine the probable inventory of damageable components in buildings of typical occupancy, 5) a spread sheet tool that enables users to implement the Vamvatsikos collapse fragility methodology; 6) a spread sheet tool that enables users to estimate collapse fragility based on collapse statistics obtained from limited numbers of analyses and 7) an electronic Performance Assessment Calculation Tool (PACT) that assists users to assemble building performance models and perform the repetitive calculations associated with the Monte Carlo analysis described above. These products are available for free from the Federal Emergency Management Agency.

5. APPLICATIONS

The FEMA P-58 performance assessment methodology has a number of important applications. The primary purpose is for assessment of the probable future performance of individual new or existing buildings. This can be done as part of a performance-based design process, or as part of assisting owners and tenants in making occupancy and ownership decisions. The methodology is being considered for use in development of a building seismic performance rating system that could be used by the lending industry as one criterion associated with loan transactions. Also the methodology can be used to assist building code developers to assess the impacts of building code requirements without having to wait for the next earthquake to occur. In assistance of the Building Seismic Safety Council, the Federal Emergency Management Agency and Applied Technology Council are presently using the methodology for this purpose by assessing the probability that buildings of different types in different seismic environments will experience damage rendering them unserviceable. This information may be used to broaden the quantification of seismic performance expectations for code-conforming buildings contained in the ASCE 7 standard.

6. FUTURE WORK

Development of the FEMA P-58 methodology represents the first step in a series of tasks identified by EERC and EERI as important contributions to development of next-generation performance-based seismic design criteria. Additional work to enhance and extend the methodology is now underway.

As noted previously, FEMA has funded the Applied Technology Council to extend the FEMA P-58 methodology to address the environmental impacts associated with building seismic performance. Impacts include CO_2 emissions, energy expenditures and solid waste generation. The extension to the methodology to address these impacts associates consequence functions for each impact with the damage states associated with each fragility group. Once completed, performance functions for these impacts will be computed in a manner analogous to repair costs and repair time.

An important next step to enable the use of the FEMA P-58 methodology in performance-based design is to identify the performance expected of typical buildings designed to present building codes. The FEMA P-58 methodology itself is an ideal tool for making this determination by evaluating the performance for a large number of code-conforming buildings. Once the performance of code-conforming structures has been quantified, it will be possible to make judgments as to whether this performance is adequate, and finally, what performance should be used as the basis for design of new buildings or upgrade of existing buildings.

If these procedures are to be practically implemented in building design, engineers and architects will need simplified tools to assist them to develop preliminary designs (step 2 in Figure 1) that are capable of meeting or nearly meeting the desired performance. Without these simplified tools, the performance-based process can be costly and tedious, rendering it impractical for use.

Finally, FEMA envisions development of companion publications targeted at building investors and owners, tenants, lenders, and insurers that will apprise them of the benefits of performance-based design approaches and provide them the information needed to take best advantage of this technique. The above simplified design guide and the companion products are the goals of a five year contract to conduct Phase 2 of the Performance Based Seismic Design Project, which has just been initiated.

REFERENCES

ASCE (2006) Seismic Rehabilitation of Existing Buildings, ASCE/SEI 41-06, American Society of Civil Engineers, Reston, Virginia

ASCE (2010) Minimum Design Loads for Buildings and Other Structures, ASCE/SEI 7-10, American Society of Civil Engineers, Reston , Virginia

Deirelein, GG (2010) Internal Project Memorandum, Estimation of Residual Drift

EERC (1996) Performance Based Seismic Design of Buildings, prepared by the Earthquake Engineering Research Center, University of California at Berkeley, for the Federal Emergency Management Agency, Report No. FEMA 283, Washington, D.C.

EERI (2000) Action Plan for Performance Based Seismic Design, prepared by the Earthquake Engineering Research Institute for the Federal Emergency Management Agency, Report No. FEMA 349, Washington, D.C.

FEMA (1997) Guidelines and Commentary for Seismic Rehabilitation of Buildings, prepared by the Applied Technology Council for the Federal Emergency Management Agency, Report No. FEMA 273/274, Washington, D.C.

FEMA (2012) Next-Generation Methodology for Seismic Performance Assessment of Buildings, prepared by the Applied Technology Council for the Federal Emergency Management Agency, Report No. FEMA P-58, Washington, D.C.

FEMA (2009) Quantification of Building Seismic Performance Factors, prepared by the Applied Technology Council for the Federal Emergency Management Agency, Report No. FEMA P-695, Washington, D.C.

Huang, YN, Whittaker, AS (2008) Internal Project Memorandum Simpliifed Analysis Procedures for Loss Prediction

ICBO (1976) Uniform Building Code, Internatioanl Conference of Building Officials, Whittier, California.

Moehle, J.P. and Deirelein, G.G., (2003) A Framework Methodology for Performance-based Earthquake Engineering, *13th World Conference on Earthquake Engineering*, **Proceedings**, Paper 679.

NIST (1999) Uniformat II Elemental Classification System for Building Specifications, Cost Estimating and Cost Analysis, Report No. NISTIR 6389, National Institute of Standards and Technology, Gaithersburg, Maryland.

Vamvatsikos, D. and Cornell, C.A. (2006) Direct Estimation of the Seismic Demand and Capacity of Oscillators with Multilinear Static Pushovers through IDA, *Earthquake Engineering and Structural Dynamics* **(35)**

Yang, T.Y., Moehle, J.P., Stodjadinivic, B. and Der Kiureghian, A. (2006) An Application of the PEER Performance-based Earthquake Engineering Methodology, *8th U.S. National Conference on Earthquake Engineering*, **Proceedings**, Paper 1448.