FEMA P58
SEISMIC PERFORMANCE ASSESSMENT OF BUILDINGS

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ABSTRACT

The FEMA P-58 methodology for seismic performance assessment of buildings was developed by the Applied Technology Council under its ATC-58 program as the first in a series of next-generation performance-based seismic design criteria and guidelines. The Federal Emergency Management Agency (FEMA) envisaged this program in the mid-1990s, as an extension of the FEMA 273/274 seismic rehabilitation guidelines and commentary. FEMA initiated the project with a series of exploratory programs, in which it sought and received broad input from the earthquake engineering community and other stakeholders. Actual development began in 2001 with technical support from the three national earthquake engineering research centers as well as individual NSF grants and a grand challenge project. The project culminated in 2012 with publication of a series of products including Volume 1 – Methodology, Volume 2 – Implementation Guide, companion software, and a series of background documents. The completed methodology permits assessment of the seismic performance of individual buildings, considering their unique characteristics, in terms of probable repair costs, repair time and casualties. A companion publication, published as a fourth Volume in the FEMA P-58 series, presents alternative approaches to add probable environmental impacts to the methodology.

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Introduction

Present performance-based seismic design procedures, embodied in the ASCE 41 [4] standard were originally developed for the FEMA 273/274 seismic rehabilitation guidelines jointly developed by the Applied Technology Council, Building Seismic Safety Council, and American Society of Civil Engineers, under Federal Emergency Management Agency (FEMA) sponsorship. Developed as part of a series of efforts to encourage and enable existing building owners to improve their buildings’ probable seismic performance, the FEMA 273/274 framework offered existing building owners the widest possible latitude in selecting seismic upgrade criteria. Under the FEMA 273/274 framework, performance was categorized into a series of 3 discrete performance levels: Immediate Occupancy, Life Safety and Collapse Prevention, 2 intermediate ranges: Damage Control and Incremental Improvement. Structural systems and nonstructural components were treated separately and independently. Owners could elect to upgrade either the structure or its nonstructural components, or both; and to any combination of performance levels and earthquakes.

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The FEMA 273/274 guidelines introduced a number of landmark concepts into structural design. First it introduced direct design to achieve targeted performance as an alternative to the building code’s indirect approach relying upon enhanced design forces and mandatory detailing practices. It popularized the concept that earthquake induced deformation was a primary factor affecting earthquake performance, ushering in a series of “displacement-based” design procedures. Next it introduced the use of nonlinear analysis as a design method, an approach previously considered only a research tool. Finally, it acknowledged the concept of uncertainty in building response prediction, adjusting both computed demands and capacities based on assessment of the engineer’s knowledge of the building’s construction and the quality and type of analysis performed.

Structural engineers and researchers regarded these approaches as both landmark and liberating and demanded extension of the procedures to new building design. Others noted that as powerful and attractive as the new procedures were, their reliability was unknown. Further, nonstructural performance was principally dealt with by requiring anchorage and bracing of components, rather than assuring that systems would remain operable and functional when this was required. Hearing both the demands for extension of the new procedures, and concerns as to their validity, in the mid-1990s, FEMA sponsored a series of efforts to develop next-generation performance-based seismic design criteria. The Earthquake Engineering Research Center at the University of California at Berkeley and the Earthquake Engineering Research Institute, independently developed action plans, published respectively as FEMA 283 [5] and FEMA 349 [6]. Both plans called for broad multi-year research and development programs that included basic structural engineering and socio-economic research components, leading up to the publication of design criteria and guidelines.

FEMA formally entered into contract with the Applied Technology Council to develop the next-generation procedures in late 2001. The resulting ATC-58 project did not include any budget for basic research, which had been major components of both the FEMA 283 and FEMA 349 action plans. However, the further development of performance-based seismic design had become a priority for the National Earthquake Hazards Reduction Program and as a result, the National Science Foundation worked cooperatively with FEMA to encourage submission of research topics related to this topic. Performance-based seismic design became the focus of studies conducted by the Pacific Earthquake Engineering Research Center (PEER) and a major component of studies conducted by the two other national centers as well. Finally NSF funded a grand challenge project focused on the performance of nonstructural building components. Thus, although lacking a research component, the ATC 58 project had extensive relevant research available to it, as the project developed its methodology and framework.

In the post 9/11 era, funding for seismic guidelines development was limited to a fraction of that envisaged under the Action Plans. Initial tasks included a series of workshops, held in 2002, to determine stakeholder needs and determine project direction. Stakeholders noted a need to express performance in terms meaningful to their decision-making processes, including repair costs, downtime and casualties. Stakeholders also advised explicit acknowledgement of uncertainties associated with the performance assessment process.

With the limited funding available, the project team recommended a two-phase effort.
The first phase was to focus on development of a performance-assessment methodology that would assess building performance in terms of probable repair costs, repair times and casualties, with explicit expression of uncertainty as suggested by stakeholders. The second phase was to provide guidelines both for engineers and other stakeholders as to how to use the new methodology to advantage in seismic risk reduction. FEMA published the resulting program plan for this two-phased effort as FEMA 445 [7]. This paper presents the products that resulted from the now complete first phase.

**Methodology**

The ATC-58 project adopted the performance-based seismic engineering framework then under development by PEER [8]. This framework expresses earthquake performance as the probable values of key performance measures, including casualties, repair costs, and occupancy loss calculated from a complex “triple integral” derived from an application of the total probability theorem. Specifically, the probable value of an earthquake loss measure is obtained from the equation:

\[
\text{Performance} = \iiint \{ \text{PM} | \text{DS} \} \{ \text{DS} | \text{EDP} \} \{ \text{EDP} | I \} dz
\]

where, \( \text{PM} \) is the value of a performance measure, e.g., repair cost, given the occurrence of a particular damage state, \( \text{DS} \); \( \text{EDP} \) (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. 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. [9] 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-58 project team ultimately adopted and expanded this approach into the FEMA P-58 methodology.

![Figure 1. Typical FEMA P58 performance function.](attachment:image.png)
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 1, termed a performance function. Key earthquake impacts addressed include: repair costs, repair time, serious injuries requiring hospitalization, deaths, and posting of the building as “unsafe,” commonly referred to as “red-tagging.” A parallel project explored expansion of these performance measures to include environmental impacts including CO₂ emissions, energy utilization and solid land fill generation associated with repair of earthquake damage. The work plan for this effort is published as Volume 4 of the FEMA P-58 series and its implementation is planned in the recently initiated second project phase.

The FEMA P-58 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, defined as a user-selected, 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 the defined event. Time-based assessments produce performance functions considering all possible earthquake scenarios and the annual occurrence frequency of each scenario, taking into account occurrence uncertainty.

**Performance Models**

The FEMA P-58 performance assessment 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 is the set of all those similar components (e.g., fire sprinkler drops and heads) 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 [10] and is fully described by a fragility specification that includes: 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. Performance groups are subsets of fragility groups and include collections of components that will be subjected to the same demand, e.g., light fixtures at the third story.

Although damage can occur in a continuous spectrum of possible states ranging from none to complete damage, the FEMA P-58 methodology uses a limited series of discrete damage states for each component type. Damage states are selected to represent that range of damage states for which there are unique consequences such as particular repair procedures, life loss probabilities, or post-earthquake occupancy consequences. For example, one damage state for exterior glazing systems is defined by compromise of the air and water integrity of the gasket; a second damage state includes cracking, but-not fall-out of the glass; a third damage state by fall-
out of the glass, and a fourth damage state, permanent distortion of the frame. The first damage state will require application of sealant; the second, replacement of the glazing; the third also entails glazing replacement, but may include some life hazards and occupancy effects, while the fourth requires replacement of the entire window unit.

Consequence functions are statistical distributions of the consequences for each damage state, accounting for uncertainty. For repair costs, the functions represent uncertainty in pricing and quantity of repair effort; for repair time, uncertainty in contractor efficiency, for casualties, uncertainty in occupant location and vitality; and for unsafe placards, uncertainty in post-earthquake inspector judgment.

The FEMA P-58 products provide fragility and consequence data for more than 700 fragility groups including a variety of structural and non-structural components. The fragility group library includes structural components of concrete, masonry, steel and wood; and nonstructural components including: building cladding and glazing systems; elevators; and mechanical, electrical and plumbing systems. Different fragility specifications are provided considering the level of seismic detailing provided, covering ordinary systems, not designed for seismic resistance to modern highly detailed systems. Typically, either peak floor acceleration or peak story drift is 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 these are known to more accurately predict damage.

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 products provide 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.

**Structural Analysis**

For intensity-based assessments, users select any 5%-damped elastic acceleration response spectrum as the basis for analysis. Computed losses will be conditioned on the occurrence of such shaking. For scenario-based assessment, users must use an appropriate ground motion prediction equation (GMPE) to determine a median spectrum for the particular event magnitude and distance, and also, dispersion associated with spectral intensity at the structure’s fundamental period. For time-based assessments, users must obtain a hazard curve for spectral acceleration at the structure’s first mode period. User’s then select intervals along this hazard curve bounded at the low end by a spectral acceleration at which damage is unlikely to occur, and at the high end, by a spectral acceleration at which there is significant probability of collapse. User’s then construct a response spectrum at the mid-point of each interval on the hazard curve.

Users employ structural analysis to predict median values of key responses parameters given a shaking intensity as well as the probable dispersion in these demands. Two analytical procedures are permitted: nonlinear dynamic analysis; and a simplified analysis method based on the ASCE 41-13 linear static procedure. The Simplified procedure is recommended only for
regular structures, without significant higher mode effects and having only moderate ductility demands. In this procedure users convert predicted story drifts and spectral accelerations into median estimates of peak floor acceleration, peak floor velocity and peak story drift, using correlation coefficients developed by Huang and Whittaker [11] based on nonlinear study of archetype structures. In this method, uncertainty is assigned based on the structure’s characteristics and the ratio of the theoretical elastic earthquake demand to the structure’s yield strength.

Nonlinear analysis can be used for any structure. Users must select a suite of ground motions and scale them for compatibility with the target spectrum (or spectra). Users then perform nonlinear dynamic analysis for each scaled ground motion. Response uncertainty, associated with record to record variability is directly computed from the suite of analyses, as are median values of peak story drift, floor acceleration and velocity. Record to record uncertainty is enriched, using judgmentally determined factors to account for modeling and ground motion uncertainties.

Residual drift is also an important parameter affecting performance. The simplified analytical method is not capable of predicting residual drift. Although nonlinear response history analysis can predict residual drift, such predictions are highly unreliable given typical models employed by engineers today. Consequently, based on study by Deirelein [12] 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.

In addition to estimates of median story drift, floor acceleration and velocity, and residual drift demands, performance assessment requires structure-specific collapse fragilities. The collapse fragility includes a median value of the first mode spectral acceleration at which collapse occurs, a dispersion, a description of the various potential collapse modes, the probability that a given mode will occur, given collapse and, an assessment of the likelihood that persons in collapsed areas will either experience death or serious injury. The median spectral acceleration and dispersion can be calculated using the procedures of FEMA P-695 [13]; the results of analyses performed as part of time-based assessment; Vamvatsikos’ [14] SPO2IDA tool; or, engineering judgment. Every structure must have at least one collapse mode, typically comprising complete collapse. Other modes can include single-story collapse, partial story collapse, or mult-story collapse. Users will generally determine the collapse modes using individual engineering judgment, informed by their analyses.

Performance Calculation

The methodology employs a Monte Carlo process to determine the probable loss distributions. The median response values and dispersions obtained from structural analysis are enriched to consider modeling dispersion and hazard uncertainty; demands are assembled into a median value vector and correlation matrix that together with the dispersions are assumed to represent a joint lognormal distribution and 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.
Figure 2 illustrates the process used to calculate losses for each realization. Each realization initiates 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. In these cases 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 the earthquake, and therefore, collapse has occurred. This information is used to determine the number of people present in the collapsed building area. The number of casualties is generated using the number of people in the collapsed area and information on the probability of deaths and serious injuries for people in the collapsed area obtained from the collapse fragility. If collapse occurs, repair costs and repair time are taken as the building replacement values.

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

Finally, a determination is made as to whether residual drift is such that the building would be deemed irreparable. For this purpose, 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. For a given realization, 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.

This process 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 more severe consequences.

Products

The FEMA P-58 methodology is published as a package of products that include Volume 1: a report describing the methodology in detail; Volume 2: an implementation guide, providing how-to instructions for engineers, illustrated with examples; Volume 3: an electronic database containing fragility and consequence functions for typical structural and non-structural building components; a spreadsheet tool that enables users to estimate an inventory of damageable components in buildings of typical occupancy; a spreadsheet tool that enables users to implement the Vamvatsikos collapse fragility methodology; a spreadsheet tool that enables users to estimate collapse fragility based on collapse statistics obtained from limited numbers of analyses; and, 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 analyses described above. These products are available for free from the Federal Emergency Management Agency.

Applications and Future Work

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, undertaken as part of a performance-based design process. The methodology can also be used to assess probable maximum losses (PMLs) associated with real estate transactions. More importantly, the methodology can be used to assist building code developers to assess the impacts of building code requirements without having to wait for future earthquakes, enabling improvement of the building code provisions.

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. These include refinement of the fragility database and enhancement and upgrade of PACT.

During development of the methodology and its companion tools, some benchmark comparisons of the performance of real buildings in earthquakes with that predicted by the
methodology were performed. Additional studies of this type were undertaken in the ATC 63-2
and 63-3 projects. These studies suggest that the methodology currently over-estimates damage
and losses relative to recent earthquake experience. Further studies of this type and calibration
of the methodology to better predict actual earthquake performance are planned as part of a
recently authorized second phase of the ATC-58 project. Once these calibrations are performed,
the project will use the methodology to identify the performance expected of typical buildings
designed to present building codes. This will enable establishment of a basis for code-
equivalency, an essential need if the methodology is to be used in design.

Finally, if these procedures are to be practically implemented in building design,
engineers will need simplified tools to assist them to develop designs that are capable of meeting
the desired performance. Without these simplified tools, the performance-based process can be
costly and tedious, rendering it impractical for use. The second phase of the ATC-58 project will
develop these tools. This project will also include 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 best take advantage of this technique.

Conclusions

The FEMA P-58 methodology, developed by the Applied Technology Council under its ATC-58
project, provides powerful new tools to assess the probable performance of individual buildings
in future earthquakes, measured in terms of potential repair costs, repair times, casualties and
environmental impacts. These tools are available for download and use from the FEMA
publications web site.

A follow-on project is currently underway. Major goals of this project include calibration
of the methodology and tools to more closely predict performance as has been seen in past
earthquakes; determine measures of code-equivalency in terms of the new performance metrics;
provide designers with guidance on how to derive designs capable of intended performance; and,
provide guidance to decision-makers on how best to take advantage of this new methodology.

Ultimately, the FEMA P-58 procedures should enable the development of more reliable
building codes; more cost effective and reliable upgrades of existing buildings; and designs for
new buildings, that will perform as desired by key decision-makers.

Acknowledgement

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