THE HORIZON FOR NEXT-GENERATION PERFORMANCE ASSESSMENT OF BUILDINGS IS HERE: FEMA P-58

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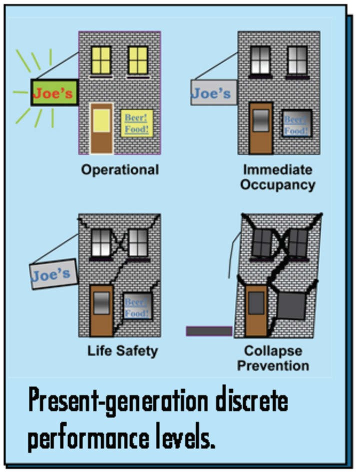
Abstract

The Applied Technology Council (ATC) has completed a program under contract with the Federal Emergency Management Agency (FEMA) for the development of next-generation seismic performance assessment. This work is the result of a 10-year effort, known as the ATC-58/ATC-58-1 Projects, resulting in the publication of FEMA P-58, *Seismic Performance Assessment of Buildings, Volume 1 – Methodology*, *Volume 2 – Implementation Guide*, and *Volume 3 – Supporting Electronic Materials and Background Documentation*. Based on the framework for performance-based seismic engineering developed by the Pacific Earthquake Engineering Research (PEER) Center, the methodology is intended for use in a performance-based seismic design process for new or existing buildings. Results are expressed as probability distributions for potential 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.

Introduction

Performance-based design in its current form originated in the 1990s. Present-generation performance-based design is based on FEMA 273, *NEHRP Guidelines for the Seismic Rehabilitation of Buildings* (FEMA, 1997), which addressed seismic strengthening of existing buildings, and outlined initial concepts of performance levels related to damageability and varying levels of seismic hazard. Its successor documents, FEMA 356, *Prestandard and Commentary for the Seismic Rehabilitation of Buildings* (FEMA, 2000), and the American Society of Civil Engineer (ASCE) Standard ASCE/SEI 41-06, *Seismic Rehabilitation of Existing Buildings* (ASCE, 2007) define current practice for performance-based seismic design in the United States.



Present-generation discrete performance levels.

In present-generation procedures, performance is expressed in terms of a series of discrete performance levels identified as Operational, Immediate Occupancy, Life Safety, and Collapse Prevention. These performance levels are applied to both structural and nonstructural components, and are assessed at a specified seismic hazard level. Although they established a vocabulary and provided a means by which engineers could quantify and communicate seismic performance to clients and other stakeholders, implementation of present-generation procedures in practice uncovered certain limitations and identified enhancements that were needed.

Limitations in present-generation procedures included: (1) questions regarding the accuracy and reliability of available analytical procedures in predicting actual building response; (2) questions regarding the level of conservatism present in acceptance criteria; (3) the inability to reliably and economically apply performance-based procedures to the design of new buildings; and (4) the need for alternative ways of communicating performance to stakeholders that is more meaningful and useful for decision-making purposes.

In order to fulfill the promise of performance-based engineering, FEMA began planning the development of next-generation procedures to address the above limitations. The objectives of the ATC-58/ATC-58-1 Projects were to:

- Develop a framework for performance assessment that properly accounts for, and adequately communicates to stakeholders, limitations in our ability to accurately predict response, and uncertainty in the level of earthquake hazard;
- Revise the discrete performance levels defined in present-generation procedures to create new performance measures that better relate to the decision-making needs of stakeholders;
- Create procedures for estimating these new performance measures for both new and existing buildings;
- Expand current nonstructural procedures to explicitly assess the damageability and post-earthquake condition of nonstructural components and systems; and
- Modify current structural procedures to assess performance based on global response parameters, so that the response of individual components does not unnecessarily control the prediction of overall structural performance.

Performance Measures

Performance assessment is the process used to determine the performance capability of a given building design. In performance assessment, engineers conduct structural analyses to predict building response to earthquake hazards and determine the potential consequences of that response. In the FEMA P-58 methodology, seismic performance is expressed in terms of probable casualties, repair and replacement costs, repair time, and unsafe placarding resulting from earthquake damage. The methodology can be expanded to consider additional consequences such as environmental impacts, and could be adapted to assess performance for other hazards and extreme loading conditions, but such enhancements have not been included in the current version of the methodology.

Each factor affecting seismic performance has significant uncertainty in our ability to know or predict specific values. The cumulative result of these and other uncertainties is that it is not possible to precisely assess the seismic performance of a building. It is, however, possible to express performance measures in the form of performance functions, as shown in Figure 1.

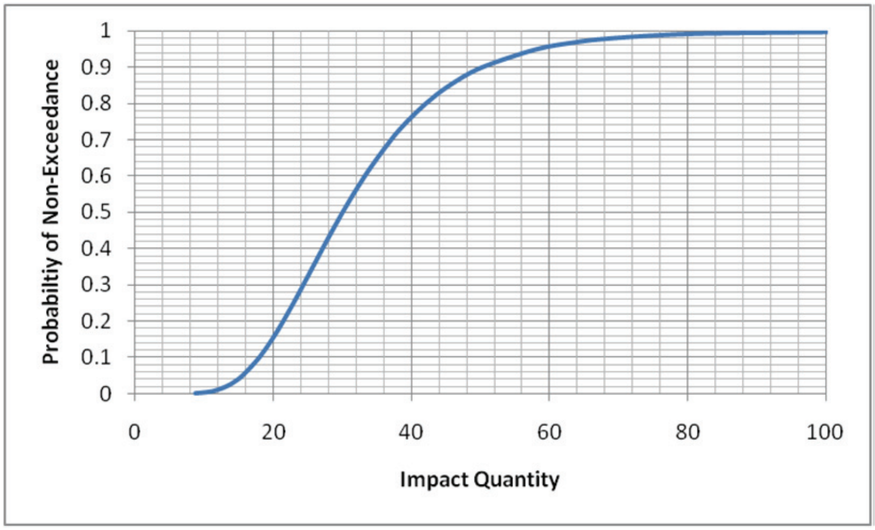


Figure 1. Hypothetical building performance function.

Performance functions are statistical distributions that indicate the probability that losses of a specified or smaller magnitude will be incurred as a result of future earthquakes. In the figure, the horizontal axis represents the size of the impact (e.g., number of casualties, repair cost, or weeks of construction time) while the vertical axis indicates the probability that the actual impact will be equal to or less than this value.

Performance measures serving as the basis for the assessment process were developed with input from an expanded group of stakeholders including commercial real estate investors, insurers, lenders, attorneys, and architects. This group was assembled at an invitational workshop held in Chicago, Illinois (ATC, 2002), and the collective opinions of this group were used to select the concepts of casualties, direct and indirect economic losses, and downtime, which are used to express and measure consequences in the methodology. The FEMA P-58 methodology and procedures describe a means to determine performance functions for these consequences.

Next-Generation Performance Assessment Process

The next-generation performance assessment process is illustrated in Figure 2. It begins much like present-generation methods with establishment of the seismic hazard (in the form of response spectra or ground motion records) and estimation of structural response (from structural analysis). From there it diverges from current procedures to include the explicit estimation of structural damage based on response quantities (drift, velocity, acceleration), and explicit estimation of consequences (casualties, repair and replacement costs, repair time, and unsafe placarding) based on damage. The key to the ability to estimate structural damage from response, and consequences from damage are the FEMA P-58 concepts of a "Building Performance Model" and "Fragility Specification."

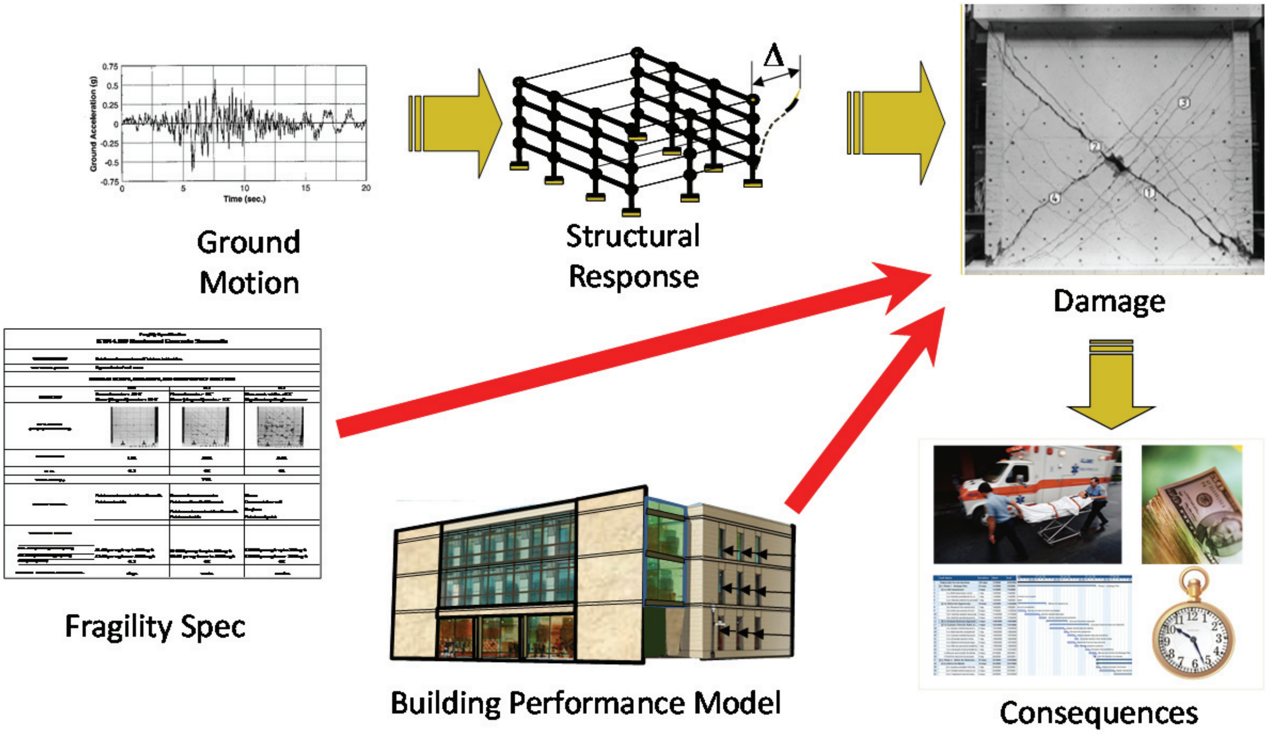


Figure 2. Next-Generation Performance Assessment Process.

Building Performance Model

The building performance model is an organized collection of data necessary to define building assets that are vulnerable to the effects of earthquake shaking. This includes definition of:

- Basic building data including building size, replacement cost, and replacement time.
- Occupancy, including the distribution of people within the building envelope and the variability of this distribution over time, and the type and quantity of nonstructural components and contents present in the building.
- Vulnerable structural and nonstructural elements and assemblies in sufficient detail to quantify their location within the building and the demands they will experience during response to earthquake shaking; their vulnerability to damage caused by earthquake-induced deformations and forces; and the consequences of this damage, in terms of collapse potential and generation of life-threatening debris, necessary repair actions, and influence on post-earthquake building occupancy due to unsafe placarding.

The building performance model includes population models, fragility groups, and performance groups. Components and assemblies that provide measurable resistance to deformation are classified as structural whether or not they are intended to be part of the gravity or seismic-force-resisting systems. Elements and components that are vulnerable to damage are assigned a fragility within the building performance model. Elements and components that are not vulnerable to damage are not included in the performance model, although the costs associated with these elements must be considered in the total building replacement cost.

Fragility Specification

Component fragility functions are statistical distributions that indicate the conditional probability of incurring damage given a value of demand. Although actual damage can occur as a result of complex relationships between component demands of various types, the occurrence of all damage states within a fragility group is predicted by a single demand parameter. The selected demand parameter is the one that best predicts the occurrence of damage with the least amount of uncertainty. For most structural systems (e.g., shear walls, steel braces, steel and concrete moment frames), and many nonstructural components, story drift ratio is the preferred demand parameter. Floor acceleration and floor velocity are also used, and it is possible to define other demand parameters (e.g., plastic rotations, axial forces) when appropriate.

Although component damage generally occurs as a continuum with the scope and extent of damage increasing as demand increases, each component fragility is assigned a series of discreet damage states to characterize the different levels of damage that can occur. Each damage state is associated with a unique set of consequences. Consequence functions are distributions of the likely consequences of a component damage state translated into repair costs, repair time, potential for unsafe placards, casualties and other impacts. For each damage state, fragility definitions include repair descriptions that provide the necessary information to develop the associated repair costs and times.

All of the damage, fragility, and consequence data associated with a fragility group are recorded in a fragility specification. Over 700 fragility specifications have been developed as part of the methodology and are available in an electronic database. Table 1 lists the structural systems for which fragility and consequence data have been provided along with the methodology. Table 2 lists the building occupancies for which information on common nonstructural components, contents, normative quantities, and population models have been provided along with the methodology.

Table 1. Structural Systems and Components for which Fragility and Consequence Data have been Provided

Material	*System*	*Details*
Concrete	Beam-column frames	Conventionally reinforced, with or without modern seismic-resistant detailing
	Shear walls	Shear or flexurally controlled, with or without seismic-resistant detailing
	Slab-column systems	Post-tensioned or conventionally reinforced, with or without slab shear reinforcement
Masonry	Walls	Special or ordinary reinforced masonry walls, controlled by shear or flexure
Steel	Moment frames	Fully restrained, pre- or post-Northridge, Special, Intermediate, and Ordinary detailing
	Concentrically braced frames	"X"-braced, chevron-braced, single diagonals, special, ordinary, or nonconforming detailing
	Eccentrically braced frames	Flexure or shear links at mid-span of link beam
	Light-framed walls	Structural panel sheathing, steel panel sheathing or diagonal strap bracing
	Conventional floor framing	Concrete-filled metal deck, untopped steel deck, or wood sheathing
Timber	Light-framed walls	Structural panel sheathing, gypsum board sheathing, cement plaster sheathing, let-in bracing, and with or without hold downs

Table 2. Building Occupancies for which Nonstructural Component Data and Population Models have been Provided

Occupancy	*Details*
Commercial Office	None
Education (K-12)	Typical elementary, middle school, high school classrooms
Healthcare	General in-patient hospitals, medical equipment excluded
Hospitality	Hotels and motels
Multi-Unit Residential	Also applicable to single-family detached housing
Research	Special purpose laboratory equipment excluded
Retail	Shopping malls and department stores
Warehouse	Inventory excluded

FEMA P-58 Methodology

The steps of the FEMA P-58 seismic performance assessment methodology are shown in Figure 3. Key steps in the methodology are briefly described below. The methodology can be used to develop three different types of performance assessment: intensity-based, scenario-based, and time-based assessments.

- Intensity-based assessments evaluate a building's probable performance assuming that it is subjected to a specified earthquake shaking intensity. Shaking intensity is defined by 5% damped, elastic acceleration response spectra. This type of assessment can be used to assess a building's performance in the event of design earthquake shaking consistent with a building code response spectrum, or to assess performance for shaking intensity represented by any other response spectrum**.**
- Scenario-based assessments evaluate a building's probable performance assuming that it is subjected to a specified earthquake scenario consisting of a specific magnitude earthquake occurring at a specific location relative to the building site. Scenario assessments may be useful for buildings located close to one or more known active faults. This type of assessment can be used to assess a building's performance in the event of a historic earthquake on these faults is repeated, or a future projected earthquake occurs.
- Time-based assessments evaluate a building's probable performance over a specified period of time (e.g., 1-year, 30-years, or 50-years) considering all the earthquakes that could occur in that time period, and the probability of occurrence associated with each earthquake. Time-based assessments consider uncertainty in the magnitude and location of future earthquakes as well as the intensity of motion resulting from these earthquakes. Assessments based on a single year are useful for cost-benefit evaluations used to decide between alternative performance criteria. Assessments over longer periods of time are useful for other decision-making purposes.

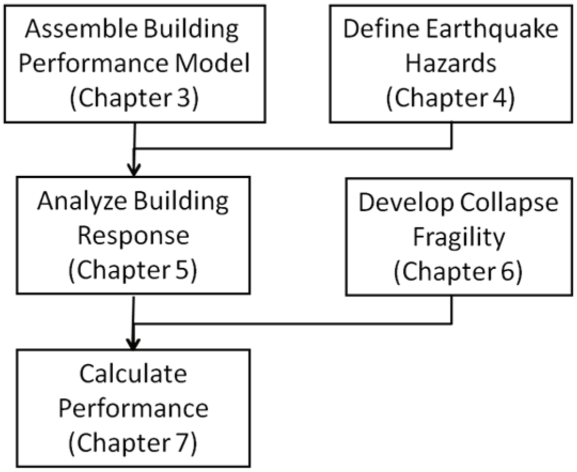


Figure 3. Flow chart of the FEMA P-58 performance assessment methodology.

Assemble Building Performance Model. The building performance model is described above. The process of assembling the building performance model involves identifying all building structural and nonstructural components that are vulnerable to damage and assigning fragility specifications to them. It also includes identification of the building population at risk.

Define Earthquake Hazards. At this time, the 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. In intensity-based assessments, for example, 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.

Analyze Building Response. Structural analysis is used to determine the probable statistical distribution of response parameter values, given an intensity of shaking. The methodology permits two analytical procedures. The preferred method consists of nonlinear dynamic analysis, using multiple suites of ground motions scaled to represent the target intensity of shaking, or the scenario event. 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.

Develop Collapse Fragility. Most earthquake casualties occur as a result of partial or total building collapse. 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. The methodology permits several alternative procedures for deriving collapse fragilities. Users can: (1) determine collapse fragilities using incremental dynamic analysis procedures contained in FEMA P-695, *Quantification of Building Seismic Performance Factors* (FEMA, 2009); (2) infer collapse fragility on the basis of the number of collapses obtained in limited suites of analyses at several intensity levels; (3) 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; or (4) establish collapse fragility using engineering judgment.

Calculate Performance. 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 modeling 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 is repeated thousands of times. Then for each consequence (e.g. repair cost) the realizations are assembled into performance functions.

In addition to the technical volumes describing the methodology and supporting documentation, an electronic calculation tool, the *Performance Assessment Calculation Tool* (PACT), has been provided to assist in the development of the building performance model, cataloging of fragility data, conduct of probabilistic calculations, and accumulation of losses necessary for implementing the methodology.

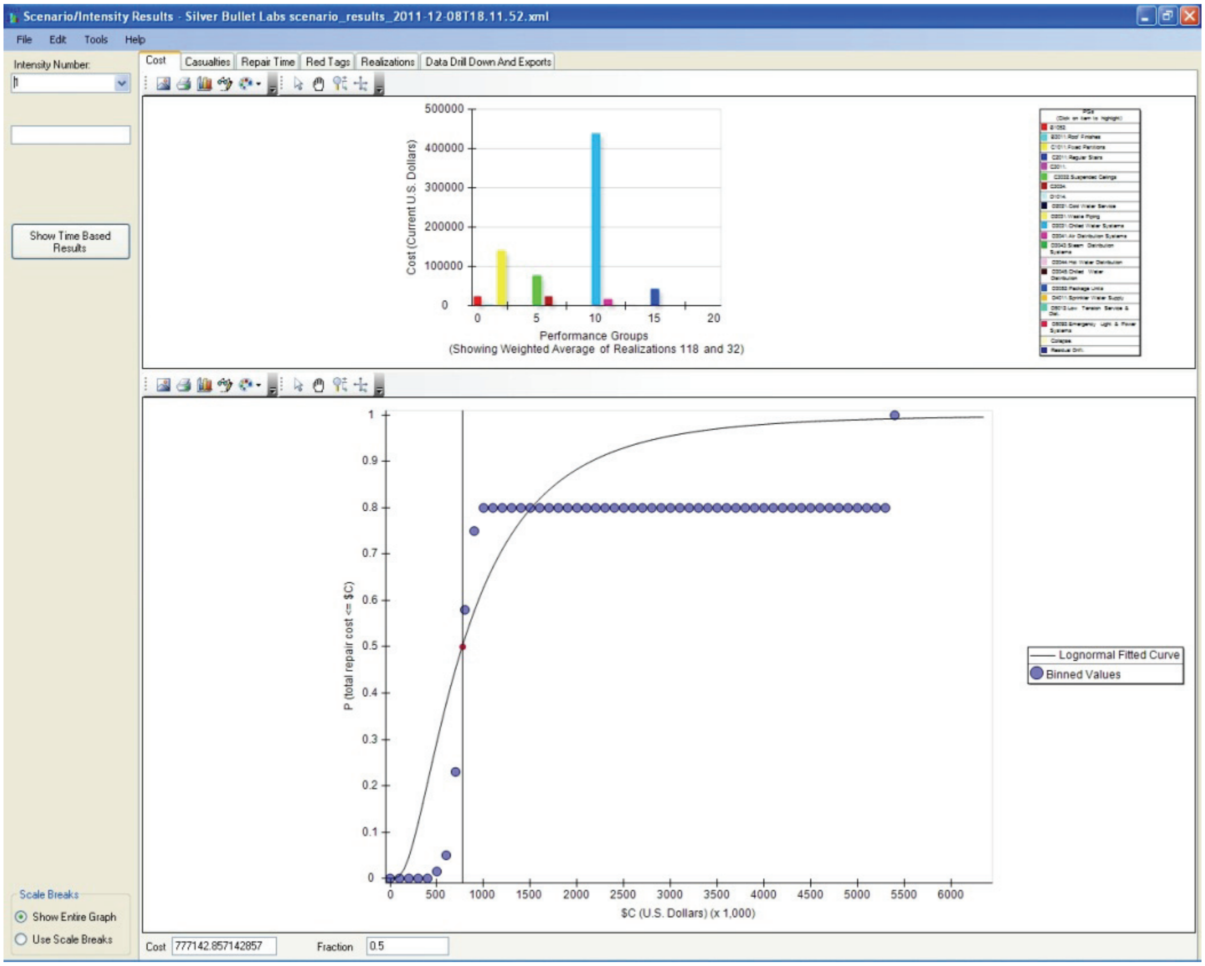
Technical Basis of the FEMA P-58 Methodology

The technical basis of the methodology is the framework for performance-based earthquake engineering developed by researchers at the Pacific Earthquake Engineering Research Center (PEER) during the period 1997–2010. The PEER framework (Moehle and Deierlein, 2004) applies the total probability theorem to predict earthquake consequences in terms of the probability of incurring particular values of performance measures or outcomes including casualties, repair costs, and downtime. Under the PEER framework, earthquake performance is computed as a multi-level integral of the probability of incurring earthquake effects of differing intensity, over all intensities; the probability of experiencing building response (drifts, accelerations, component demands) of different levels, given an intensity of shaking; the probability of incurring damage of different types, given building response; and the probability of incurring specific consequences given that the damage occurs. In 2004, an application of this framework was developed utilizing a modified Monte Carlo approach to implement the integration using inferred statistical distributions of building response obtained from limited suites of analyses. This application, described in

Yang et al. (2009), is the basis of the performance assessment calculations and accumulation of consequences as implemented in the methodology.

Performance Assessment Calculation Tool – Sample Results

The *Performance Assessment Calculation Tool* (PACT) provides a range of options for viewing assessment results, or printing out hard copy reports. In addition to providing composite results considering all performance groups and demand input from both building directions, PACT can parse results by performance group, direction, story level, and realization for each performance measure including repair cost, repair time, casualties, and unsafe placarding. Sample PACT results for repair cost are shown in Figure 4.



Intensity Number: 1

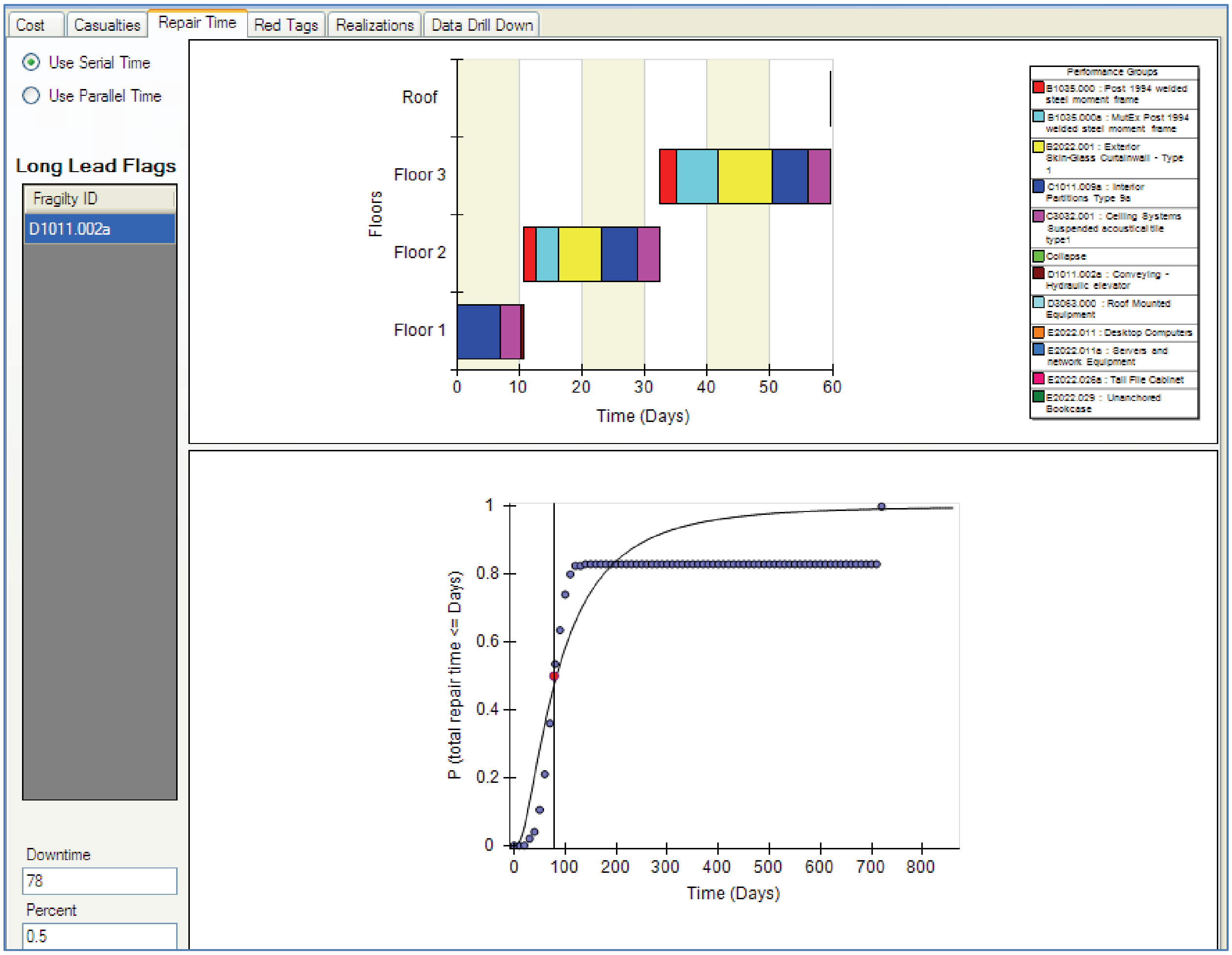
Cost 777142.857142857

Fraction 0.5

Figure 4. Sample PACT results for repair cost.

The upper portion of the figure shows the contribution to repair cost attributable to each performance group. The lower portion of the figure shows the realization data generating the performance function for repair costs. The horizontal axis is the dollar value of repair cost, and the vertical axis is the probability of non-exceedance (probability that total repair costs will be less than or equal to the dollar value).

Sample PACT results for repair time are shown in Figure 5. Estimates of repair time are related to repair costs. Two options are provided: one assuming the work is performed in parallel and one assuming the work is performed in series.



● Use Serial Time
○ Use Parallel Time

Long Lead Flags

Fragilty ID
D1011.002a

Downtime: 78

Percent: 0.5

Figure 5. Sample PACT results for repair time.

The upper portion of the figure shows the contribution to repair time attributable to each performance group. In this illustration, the serial option is shown, and the work is assumed to occur in series. The lower portion of the figure shows the realization data generating the performance function, with repair time on the horizontal axis and probability of non-exceedance on the vertical axis.

Similar plots can be obtained for other consequences. Information presented in this form can be used to assess the probable performance of individual buildings in a manner that stakeholders can use to make informed decisions about capital investment and building design requirements. Information on potential losses can be used by building owners to make decisions on earthquake insurance, cost-benefit evaluations between different design criteria, and the need to retrofit for improved earthquake performance to minimize business interruption costs. Information on the losses attributable to each performance group can be used by design professionals in a performance-based design process to adjust the design to minimize losses or to achieve higher performance objectives. Finally, the methodology can be used by building code developers to assess the impacts of building code requirements on performance, and refine code provisions to better match performance expectations, before the next earthquake occurs.

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