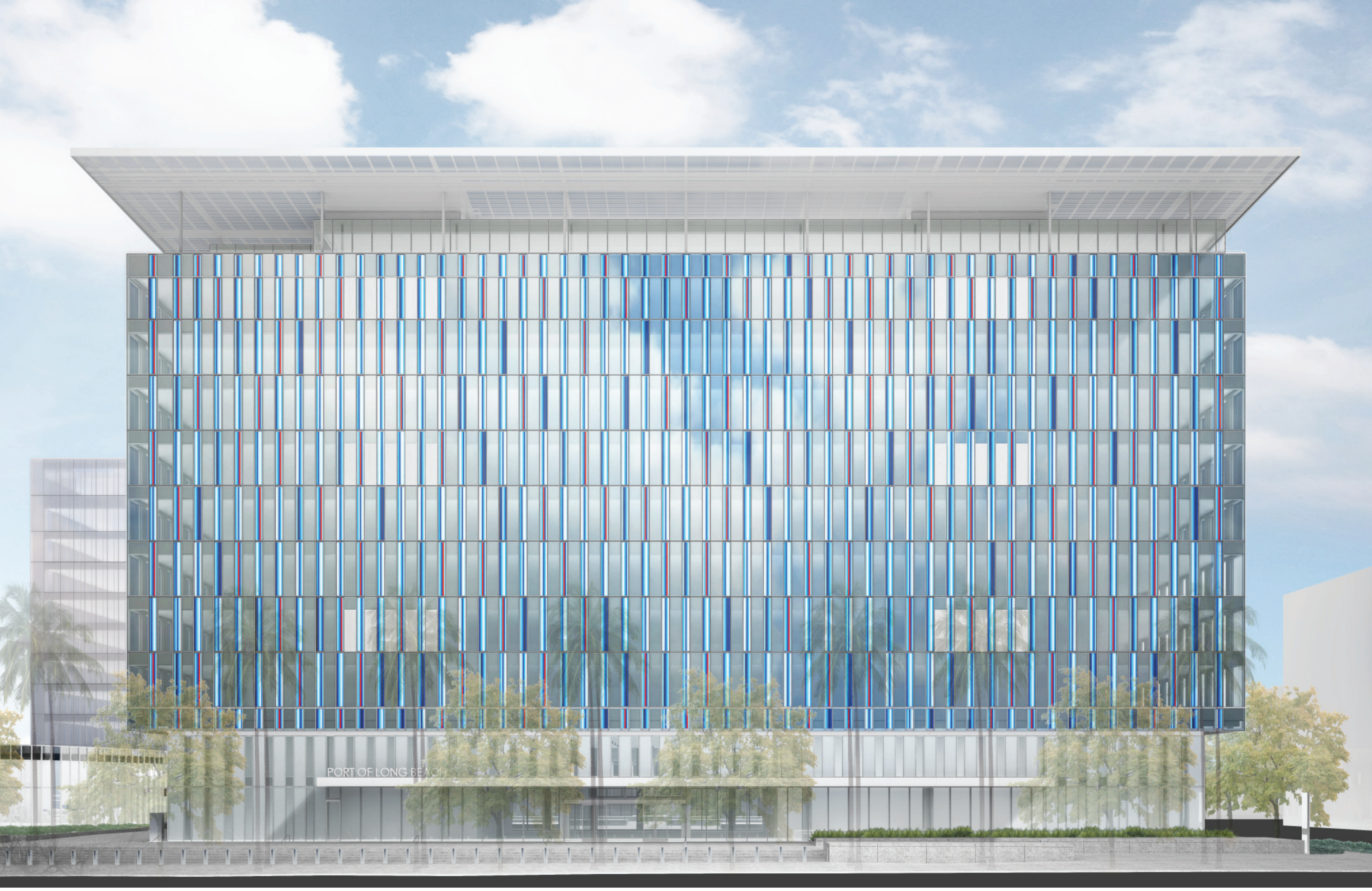

Guidelines for Performance-Based Seismic Design of Buildings

FEMA P-58-6 / December 2018

FEMA

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Guidelines for Performance-Based Seismic Design of Buildings

Prepared by

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Notice

Foreword

The Federal Emergency Management Agency (FEMA) is committed to reducing the ever-increasing cost that disasters inflict on our country. Preventing losses before they happen, by building to withstand anticipated forces, is one of the key components of mitigation, and is the only truly effective way of reducing the impact of disasters on our country. One of the most promising tools that can be used to reduce damage from an earthquake, or other similar disasters, is Performance-Based Seismic Design (PBSD).

PBSD is a concept that permits the design and construction of buildings with a realistic and reliable understanding of the risk to life, occupancy, and economic loss that may occur as a result of future earthquakes. PBSD is based on an assessment of a building's design to determine the probability of experiencing different types of losses, considering the range of potential earthquakes that may affect the structure. This allows a building owner or regulator to select the desired performance goal for their building.

Current building codes are prescriptive in nature and are principally intended to provide a life-safety level of protection when a design-level event, such as an earthquake, occurs. While building codes are intended to produce structures that meet a life-safety performance level for a specified level of ground shaking, they do not provide designers with a means to determine if other performance levels would be achieved. During a design level earthquake, a code-designed building could achieve the goal of preventing loss of life or life-threatening injury to building occupants, but could still sustain extensive structural and nonstructural damage and be out of service for an extended period of time. In some cases, the damage may be too costly to repair, leaving demolition as the only option.

Phase 1 of this project, completed in 2012, resulted in the publication of FEMA P-58, *Seismic Performance Assessment of Buildings, Volume 1 – Methodology*, *Volume 2 – Implementation Guide*, and a series of supporting electronic materials and background technical information. For practical implementation of the methodology, this included the development of an electronic tool, referred to as the *Performance Assessment Calculation Tool*, or PACT, to help capture building inventory data, input a given earthquake shaking probability or intensity, apply specific fragilities and consequences to each building component, and present the results of a large number of runs, or realizations, in a logical format.

The FEMA P-58 methodology utilizes performance measures that can be understood by decision makers. These performance measures relate the amount of damage to the building and the consequences of that damage including: potential casualties; loss of use or occupancy; and repair and reconstruction costs.

Phase 2 of this project utilized the FEMA P-58 seismic performance assessment methodology to develop performance-based seismic design guidelines and stakeholder guidelines. This five-year effort included the development of the following products:

- *Seismic Performance Assessment of Buildings, Volume 4 – Methodology for Assessing Environmental Impacts*, which describes a recommended methodology for incorporating assessment of environmental impacts, along with other consequences, that are associated with the repair of damage caused by earthquake shaking.
- *Seismic Performance Assessment of Buildings, Volume 5 – Expected Seismic Performance of Code-Conforming Buildings*, which applies the FEMA P-58 seismic performance assessment methodology to a series of building archetypes representative of structures conforming to the seismic provisions of the current building code to quantify the expected seismic performance of code-conforming buildings, identify factors that contribute to seismic performance, and provide the technical basis for simplified performance-based design guidance.
- *Guidelines for Performance-Based Seismic Design of Buildings*, which is a design guideline that provides guidance to design professionals on the implementation of performance based seismic design of buildings using the FEMA P-58 methodology, including: the performance-based seismic design process; selection of appropriate performance objectives; selection of seismic-force-resisting systems; determining appropriate stiffness and strength; and final verification of design adequacy.
- *Building the Performance You Need: A Guide to State-of-the-Art Tools for Seismic Design and Assessment*, which presents information that project managers and decision-makers need to know to use a performance-based approach for seismic design and assessment.

FEMA wishes to express its sincere gratitude to all who were involved in this project and in the development of the FEMA P-58 Phase 2 methodology. It is not possible to acknowledge the entire development team here. However, special thanks are extended to: Ronald Hamburger, Project Technical Director; John Gillengerten, Performance Products Team Leader; John Hooper, Products Update Team Leader; Laura Samant, Stakeholder Products Team Leader; William Holmes, Steering Committee Chair; and Jon Heinz and Ayse Hortacsu, ATC Project Managers. The hard work and dedication of these individuals, and all who were involved in this project, have immeasurably helped our nation move towards making performance-based seismic design a reality, and towards reducing losses suffered by the citizens of our country in future earthquakes.

Federal Emergency Management Agency

Preface

In 2001, the Applied Technology Council (ATC) was awarded the first in a series of contracts with the Federal Emergency Management Agency (FEMA) to develop Next-Generation Performance-Based Seismic Design Guidelines for New and Existing Buildings. These would become known as the ATC-58 series of projects. The overall program was separated into two major phases of work: Phase 1 – Developing a Methodology for Assessing the Seismic Performance of Buildings; and Phase 2 – Developing Performance-Based Seismic Design Procedures and Guidelines.

Development of the Phase 1 assessment methodology was completed in 2012 with the publication of the series of volumes collectively referred to as FEMA P-58, *Seismic Performance Assessment of Buildings, Methodology and Implementation*:

- FEMA P-58-1, *Seismic Performance Assessment of Buildings, Volume 1 – Methodology* (FEMA, 2012a)
- FEMA P-58-2, *Seismic Performance Assessment of Buildings, Volume 2 – Implementation Guide* (FEMA, 2012b)
- FEMA P-58-3, *Seismic Performance Assessment of Buildings, Volume 3 – Supporting Electronic Materials and Background Documentation* (FEMA, 2012c)

In the FEMA P-58 methodology, performance is measured in terms of the probability of incurring casualties, repair and replacement costs, repair time, and unsafe placarding. Since its initial development, the methodology has been expanded to include the probability of generating environmental impacts, including additional embodied energy and carbon.

Upon completion of Phase 1, work began on Phase 2. The purpose of the five-year Phase 2 work effort was to utilize the FEMA P-58 methodology in developing guidelines and recommendations for specifying seismic performance objectives in terms of FEMA P-58 performance metrics, and for selecting appropriate structural and nonstructural systems, configurations, and characteristics necessary to achieve the desired performance in varying regions of seismicity. As part of this work, the FEMA P-58 methodology was exercised in assessing the performance of code-conforming buildings.

Technical improvements and updates to the methodology were developed, as necessary, to take advantage of the latest research and to bring results into better alignment with expectations based on performance of buildings observed in past earthquakes. Phase 2 also included the development of products for communicating seismic performance to stakeholders, and assisting decision-makers in choosing between seismic design criteria and making seismic design decisions.

This report, *Guidelines for Performance-Based Seismic Design of Buildings*, is one in a series of additional volumes developed under Phase 2 intended to expand and complete FEMA P-58 series of products. It describes a performance-based seismic design process to enable design of buildings capable of meeting user-selected performance objectives, defined in accordance with the FEMA P-58 performance measures.

The FEMA P-58 series of products is the result of the collaborative effort of more than 200 individuals, across all phases of work, that were involved in the development of the underlying methodology and subsequent products and reports. ATC is particularly indebted to the Phase 2 leadership of Ron Hamburger (Project Technical Director), John Gillengerten (Performance Products Team Leader), John Hooper (Products Update Team Leader), Laura Samant (Stakeholder Products Team Leader), and the members of the Project Management Committee, including Bill Holmes (Steering Committee Chair), Steve Mahin, Jack Moehle, Khalid Mosalam, and Steve Winkel.

ATC would also like to thank the members of the Project Steering Committee, the Performance Products Team, the Products Update Team, the Stakeholder Products Team, and the many consultants who assisted these teams as part of the Phase 2 work effort. The names of individuals who served on these groups, along with their affiliations, are provided in the list of Project Participants at the end of this report.

ATC also gratefully acknowledges Michael Mahoney (FEMA Project Officer) and Robert Hanson (FEMA Technical Monitor) for their input and guidance in the conduct of this work, and Carrie Perna for ATC report production services.

Ayse Hortacsu	Jon A. Heintz
ATC Director of Projects	ATC Executive Director

Dedication

This report, one in the collection of reports comprising the FEMA P-58, *Seismic Performance Assessment of Buildings, Methodology and Implementation*, is dedicated to the memory of Stephen A. Mahin, longtime faculty member at the University of California, Berkeley.

Stephen A. Mahin

Steve brought a creative approach and limitless enthusiasm to research in structural earthquake engineering. With broad expertise in the behavior and design of structural steel, reinforced concrete, and timber construction, he also had a particular interest in numerical modeling and computer simulation.

Steve was Director of the Pacific Earthquake Engineering Research Center (PEER) from 2009 to 2015. It was during his tenure as Director, and with his passion for performance-based analysis and design, that he became involved in the ATC-58 Project. Steve was a contributor to the development of the PEER framework for performance-based earthquake engineering, on which the FEMA P-58 methodology is based, and he dedicated much of his research to testing the limits of the methodology, and to finding new and creative ways to utilize it in seismic performance assessment and design optimization.

Following the 1994 Northridge earthquake, Steve, along with Ron Hamburger and James Malley, led the FEMA-funded SAC Steel Project, a collaborative effort among the Structural Engineers Association of California (SEAOC), the Applied Technology Council (ATC), and the Consortium of Universities for Research in Earthquake Engineering (CUREE), investigating earthquake damage discovered in steel moment frame buildings. This work resulted in a series of FEMA publications on innovative solutions for evaluating and repairing existing steel moment frame connections, and procedures for reliably designing new connections, and was just one of Steve's many significant contributions to the structural engineering profession.

Steve contributed to innovation and idea sharing on a global scale. He never hesitated to share his time and insight with students, fellow researchers, practitioners, and public officials. Countless individuals and organizations have benefitted from his support, guidance, and wisdom. His creative spirit and generosity will not be forgotten.

Table of Contents

List of Figures

List of Tables

Chapter 1

Introduction

This report is the sixth in a series of volumes comprising the FEMA P-58, *Seismic Performance Assessment of Buildings, Methodology and Implementation* (FEMA, 2012; 2018). The purpose of this volume is to provide guidance to structural engineers on implementation of performance-based seismic design of buildings using the FEMA P-58 methodology. Guidance is provided in the following areas of performance-based design:

- Assisting decision-makers in selecting appropriate performance objectives for buildings of different occupancies.
- Identifying appropriate structural and nonstructural design strategies to achieve specific performance objectives.
- Developing preliminary designs to achieve selected performance objectives with minimal iteration during the design process.

1.1 Designing for Performance

The first building codes in the United States were developed and adopted in the late 1800s and early 1900s in reaction to the frequent urban conflagrations experienced in larger cities. These conflagrations resulted from the common use of open flames for cooking, heating, and lighting, the predominance of wood frame construction, and the dense construction in urban areas. Accordingly, early building codes were written to protect public safety and welfare by reducing the risk of urban conflagrations through limitations on the use of exposed wood frame construction, requirements for parapets to minimize the spread of flames from one roof to another, and other measures.

Later versions of codes included consideration of other building safety issues such as collapse due to structural overload. For most structural loading, other than earthquake, building codes address two performance levels: (1) a *service level*, which is a state such that deflections do not exceed levels detrimental to normal intended use and damage does not occur; and (2) an *ultimate level*, which is a state of failure. These performance levels are used to ensure that structures remain at the service level for routine loading given normal occupancy and likely environmental effects, and to ensure a low probability that the ultimate level will ever be experienced, so that structural failure resulting in injury or loss of life is unlikely to occur.

In the early twentieth century, following damaging earthquake events in California, Japan, and Italy, development of building code requirements for seismic resistance began. Initial seismic requirements were developed as a series of rules intended to avoid further construction of building features that were observed to lead to life-threatening damage, such as requirements to positively attach exterior masonry walls to floors and roofs to avoid out-of-plane failure of brick walls.

The underlying philosophy of current building codes is minimizing hazard to life. Important facilities are designed to enhanced criteria.

Over time, it was observed that, even in the most seismically active regions of the United States, some buildings were able to experience overstress and damage without life-threatening failure. Because damaging earthquakes are rare events that may not occur during expected life of a building, and for reasons of economy, building codes adopted a philosophy of permitting structural and nonstructural damage that does not result in a significant potential for life safety endangerment. This remains the underlying objective of building code requirements for most building occupancies in the present day.

In the 1971 San Fernando earthquake, the electrical power, water, and telephone utility systems of several hospitals were damaged, rendering the facilities unusable. Following this event, the building code community realized that ensuring life safety protection through the avoidance of structural collapse alone did not meet the public's needs for important facilities, such as hospitals, and that important facilities should be designed for enhanced criteria that would allow them to remain functional following most earthquakes. Design criteria for normal occupancy buildings remained unchanged.

Following a chain of moderate magnitude, but damaging earthquakes that struck California during the 1980s and 1990s, building owners and tenants sought information on the adequacy of their buildings to survive without collapse or support continued operation in the event of future earthquakes. Engineers were asked to evaluate earthquake risk, to predict how the buildings would perform in terms of potential risk to life, and to design building retrofits, if necessary, to improve expected performance. In response to this need, the Federal Emergency Management Agency supported development of a series of tools to assist in identifying and mitigating earthquake risk, including FEMA 273/274, *NEHRP Guidelines for Seismic Rehabilitation of Buildings* (*and Commentary*) (FEMA, 1997a; 1997b).

The FEMA 273/274 *Guidelines and Commentary* introduced a new seismic design process, now known as performance-based seismic design, that is substantially different from prescriptive design to building code provisions. In prescriptive design, the engineer must ensure that the building design conforms to a series of code requirements that regulate building configuration, structural system and detailing, and minimum lateral strength and stiffness. Buildings designed in conformance with these rules are presumed capable of meeting the performance expectations of the building code. Building owners and engineers, however, often to not have a good understanding of code performance expectations, and, typically, the performance capability of the design is neither evaluated, nor communicated, as part of the design process. In contrast, performance-based design initiates with an explicit definition of the desired performance, and the design is explicitly evaluated to demonstrate that the desired performance can be achieved. The resulting design may or may not conform to the prescriptive requirements of the building code, but it is expected to reliably meet the stated performance objectives.

> Performance-based design initiates with the definition of the desired performance, and then the design is developed to achieve this performance.

The FEMA 273/274 *Guidelines and Commentary* were subsequently updated and accepted as a standard by the American Society of Civil Engineers as ASCE/SEI 41-06, *Seismic Rehabilitation of Existing Buildings* (ASCE, 2007). More recently, performance-based seismic design is frequently used in the design of important buildings, including many tall buildings in the western United States. Design of such buildings generally follows the approach outlined in *Guidelines for Performance-Based Seismic Design of Tall Buildings* (PEER, 2017), or *An Alternative Procedure for Seismic Analysis and Design of Tall Buildings Located in the Los Angeles Region* (LATBSDC, 2017). In this report, performance-based design procedures embodied in these, and earlier documents, are referred to as first-generation procedures.

First-generation procedures focus primarily on structural performance, and nonstructural components are only evaluated for adequacy of attachment to the structure, without concern as to whether the components become damaged or remain functional. First-generation procedures characterize performance as discrete levels (Immediate Occupancy, Life Safety, and Collapse Prevention) coupled with specific earthquake intensity levels. These performance levels qualitatively describe the severity of damage that a building might sustain, but they are not quantitatively defined in terms that are important to stakeholders.

The FEMA P-58 methodology described in this report represents a next-generation performance-based seismic design procedure with the following advances from first-generation procedures:

- Performance is communicated using metrics that are more directly usable and important to stakeholders, including repair cost, repair time, environmental impacts, unsafe placarding, and casualties. This information enables stakeholders to make better decisions regarding appropriate performance objectives for their buildings.
- Performance is expressed in probabilistic terms, acknowledging the considerable uncertainties that are inherent in prediction of earthquake performance, affording designers some protection if actual building performance in an earthquake is less than specified.
- The performance of nonstructural components and systems is explicitly evaluated, resulting in a more complete characterization of actual earthquake risk.

Performance-based design is not unique to seismic design, and has been in use for many years to design resistance to terrorist attacks. It has also been used in the design of structural fire resistance and safety. In addition, the wind engineering community is in the early stages of developing performance-based design procedures for wind effects.

1.2 FEMA P-58 Methodology

The FEMA P-58 methodology enables assessment of the probable seismic performance of new or existing buildings based on their unique site, structural, nonstructural, and occupancy characteristics. This section provides a brief overview of the methodology.

First published in 2012, the FEMA P-58 *Seismic Performance of Buildings, Methodology and Implementation* has been updated and expanded in 2018 to include the following:

- FEMA P-58-1, *Seismic Performance Assessment of Buildings, Volume 1 – Methodology, Second Edition* (FEMA, 2018a)
- FEMA P-58-2, *Seismic Performance Assessment of Buildings, Volume 2 – Implementation Guide, Second Edition* (FEMA, 2018b)
- FEMA P-58-3, *Seismic Performance Assessment of Buildings, Volume 3 – Supporting Electronic Materials and Background Documentation, Third Edition* (FEMA, 2018c)

- FEMA P-58-4, *Seismic Performance Assessment of Buildings, Volume 4 – Methodology for Assessing Environmental Impacts* (FEMA, 2018d)
- FEMA P-58-5, *Seismic Performance Assessment of Buildings, Volume 5 – Expected Seismic Performance of Code-Conforming Buildings* (FEMA, 2018e)
- FEMA P-58-6, Guidelines for Performance-Based Seismic Design of Buildings (FEMA, 2018f)
- FEMA P-58-7, *Building the Performance You Need, A Guide to State-of-the-Art Tools for Seismic Design and Assessment* (FEMA, 2018g)

Volume 1 provides a complete description of the methodology and Volume 2 illustrates its implementation. Volume 3 provides a series of tools and supporting electronic materials to facilitate its use. This report (Volume 6) describes a performance-based seismic design process to enable the efficient design of buildings that are capable of meeting user-selected performance objectives defined in accordance with FEMA P-58 performance metrics.

As outlined in Volume 1, the primary steps in the FEMA P-58 methodology are to:

- Assemble Building Performance Model: A building performance model is an organized collection of data used to define the building assets at risk and their exposure to seismic hazards. Volume 3 provides two electronic tools to help define the building performance model: (1) the *Normative Quantity Estimation Tool* provides approximate quantities based on building occupancy and square footage; and (2) the *Fragility Database* includes specifications for many architectural components, common contents found in residential and office occupancies, and structural systems, both code conforming, and non-conforming. Fragility specification associated with the building's Seismic Design Category should be selected.
- Define Earthquake Hazards: Earthquake hazard is a quantification of the intensity of ground shaking and the site-specific probability that effects of a given intensity will be experienced. Ground shaking hazards are specified in different ways, depending on the type of assessment and the type of structural analysis used to quantify earthquake response.
- Analyze Building Response: Structural analysis is used to predict the response of a building to earthquake shaking in the form of response quantities (i.e., demands) that can be associated with structural and nonstructural damage. Analysis is conducted using nonlinear response

history analysis for suites of ground motions, or simplified linear analysis, to predict median values of key response quantities including peak transient and residual story drift, peak floor velocity, and peak floor acceleration at each building level in each of two orthogonal directions.

- Calculate Performance: To account for the many uncertainties in factors affecting seismic performance, the FEMA P-58 methodology uses a Monte Carlo procedure to perform loss calculations. The process involves forming hundreds to thousands of realizations for each ground motion intensity. Each realization represents one possible outcome of the building's response to ground shaking, and is generated by randomly varying the demands, component damage, and consequences, consistent with the median values and dispersions defined in the building performance model and building response simulation. Volume 1 describes this process in detail. Volume 3 provides a *Performance Assessment Calculation Tool* (PACT) that is capable of generating realizations and performing loss calculations. Proprietary software is also available through a licensing agreement with individual developers.

Regardless of the method of calculation, the output of a FEMA P-58 assessment includes probabilistic estimates of:

- Median repair cost and dispersion
- Median repair time and dispersion
- Median global warming potential and dispersion
- Median embodied energy and dispersion
- Probability of incurring serious injuries or fatalities
- Probability that the building will be posted with an unsafe placard

From probabilistic distributions of repair cost, repair time and other performance measures, it is possible to generate best estimate values (means) and estimates at any desired confidence level, for example, 90% probability of non-exceedance. In addition to providing estimates of probable consequences, calculation procedures are designed to provide information on components and systems (i.e., fragility groups) that contribute significantly to these consequences (i.e., losses). Using this information, components that are significant contributors to loss can be targeted, and a preliminary design can be effectively revised to obtain the desired performance.

1.3 Basis for Design Guidance

The design guidance in this report is based on information contained in FEMA P-58, Volume 5, which summarizes a study of the expected seismic performance of archetypical buildings designed to the requirements of ASCE/SEI 7-10, *Minimum Design Loads for Buildings and Other Structures*, (ASCE, 2010). The study assessed a wide range of buildings meeting ASCE/SEI 7-10 structural and nonstructural seismic design requirements in regions of high seismicity, and included buildings with different structural systems, Risk Categories, levels of seismic hazard, building height, and occupancies.

The purpose of the study was to quantify the expected seismic performance of code-conforming buildings in terms of FEMA P-58 performance metrics, identify factors that contribute to seismic performance, and provide a technical basis for the development of performance objectives and performance-based design guidance using the FEMA P-58 methodology.

It was found that in general, performance varies significantly across the range of code-complying systems, and that structural and nonstructural design decisions can have a measurable impact on the resulting performance. Although traditional code performance expectations focus on safety, current design requirements were shown to provide some measure of protection of property.

1.4 Limitations

Preliminary design guidance and recommendations presented herein are approximate, and appropriate to engineering calculations performed in preliminary stages of design. Tools and techniques provided in this report should be considered useful in the context of preliminary design, and not more. It is expected that building designs will continue to evolve in later stages of design, and that the actual performance capability will be verified against the desired performance objectives using a general application of the FEMA P-58 methodology on a final version of the design.

This report presents a number of “short cuts” to the FEMA P-58 methodology that are appropriate for use in preliminary design. It should be noted that these short cuts are not intended for general application of the methodology, nor for verification of the performance capability of the final design. The complete FEMA P-58 methodology, as presented in FEMA P-58, Volumes 1, 2, and 3 should be used for final performance verification.

The performance of buildings in earthquakes is highly uncertain and dependent on many factors, some of which can be controlled by the engineer during the design process (such as structural system selection, configuration, proportioning, and detailing) and others which cannot. Factors that cannot be controlled include architectural configuration, quality of structural construction, quality of nonstructural component installation, building maintenance, and character and intensity of the ground motion itself.

Design guidance presented herein has been based on a study of probable seismic performance of buildings with regular configuration, typical quality of design and construction, and subjected to typical earthquake ground motions of a specified intensity. Even in conditions constrained by these assumptions, the actual performance of an individual building in an earthquake can vary considerably. Although state-of-the-art techniques were used to evaluate the effects of design decisions on probable building performance, no warranty is offered that designs conducted in accordance with this guidance will perform within the range of expected performance.

The FEMA P-58 methodology expresses performance in a probabilistic manner, acknowledging potential uncertainties and their effects on performance. Engineers are cautioned to relate to clients, and others relying on this information, that earthquake performance prediction is inherently uncertain, and that actual performance may vary from the performance predicted using these recommendations.

1.5 Organization and Content

This volume presents guidance for structural engineers on the implementation of performance-based seismic design of buildings using the FEMA P-58 methodology.

Chapter 2 provides an overview of the performance-based seismic design process and its uses in seismic design and retrofit of buildings.

Chapter 3 provides guidance in establishing seismic performance objectives used as the basis for performance-based seismic design.

Chapter 4 discusses factors affecting performance, presents two procedures for developing a preliminary design, and provides guidance on final design and performance verification.

Appendix A provides instructions for the use of the *Performance Estimation Tool* (PET), as described in Chapter 4.

References and a list of project participants are provided at the end of this report.

Chapter 2

Implementing Performance-Based Seismic Design

Performance-based seismic design is an alternative to code-based prescriptive design procedures. In performance-based design, rather than demonstrating conformance with applicable building code requirements, engineers must explicitly demonstrate that a design will provide a defined level of performance. Some buildings designed using performance-based procedures will conform to prescriptive requirements of the building code, while others may not completely conform to these requirements.

This chapter discusses the use of performance-based seismic design, approval of designs, and an overview of the performance-based design process.

2.1 Use of Performance-Based Seismic Design

Performance-based seismic design is applicable to new or existing buildings and can be used to: (1) assess the probable seismic performance of a given building; (2) design new buildings capable of providing a desired performance; or (3) design seismic upgrades for existing buildings to improve their performance.

2.1.1 Voluntary Seismic Upgrade

Because existing buildings were designed to an earlier version of the code (or no building code at all), owners of existing buildings are more likely to be aware that their building may not perform as well as a new building, and may not provide an acceptable level of performance. Often, owners of existing buildings will ask an engineer to evaluate their building and assess its likely performance. As a result of an evaluation, an owner may decide that the assessed performance is unsuitable for the intended use of the building, and may voluntarily elect to have the building upgraded to improve its performance.

Individual stakeholders can define acceptable performance in different ways. Some stakeholders may be primarily interested in the safety of building occupants. Other stakeholders may wish to minimize potential disruption of occupancy and use following an earthquake. Others may be interested in maintaining probable repair costs below specific levels, often expressed as a percentage of building replacement cost. Acceptable performance in terms of repair costs below certain threshold values is a type of performance measure that is often used by mortgage lenders, who factor such information in lending and financing decisions.

2.1.2 Mandatory Seismic Upgrade

Many communities have adopted ordinances requiring seismic upgrade of vulnerable buildings types, characterized by structural system, age, configuration, occupancy, or unacceptable performance in past earthquakes. Building types that are commonly the target of mandatory retrofit ordinances include: unreinforced masonry bearing wall structures, older concrete tilt-up buildings, nonductile concrete frame buildings, and wood-frame buildings having soft first stories or unbraced cripple walls. Many building codes also require that buildings undergoing substantial alteration, addition, or repair be upgraded to conform to the current code for new buildings, or, depending on the extent of work, to some fraction of strength required by the current code.

Most mandatory retrofit ordinances specify prescriptive requirements for design of upgrades. Some ordinances specifically allow performance-based approaches, such as those in ASCE/SEI 41-13, *Seismic Evaluation and Retrofit of Existing Buildings*, (ASCE, 2013) or other approved design criteria documents. Even when mandatory retrofit requirements do not specifically allow (or require) performance-based design, it may be possible to use such an approach if it can be demonstrated that the resulting performance is equivalent, or superior, to prescriptive requirements. Upgrades designed using alternative performance-based criteria can be less costly and less difficult to construct than upgrades designed using prescriptive criteria.

2.1.3 Enhanced New Building Design

Most owners or developers of buildings designed and constructed in accordance with the applicable building code believe that this provides all the protection that they need against potential earthquake damage. Some owners or developers commissioning new buildings will intentionally specify designs that achieve performance that is better than what is expected for prescriptively designed buildings. Owners requesting such designs tend to be larger institutions, corporations, and government agencies with both the understanding of the potential performance of generic code-conforming buildings and the perceived need for buildings that perform better.

Enhanced new building designs, however, are not a typical request because most owners or developers are unaware that code-conforming buildings are designed with the expectation of damage in an earthquake. Depending on the use of a building, it may be necessary for an engineer, or architect as the lead design professional, to educate owners on the expected performance of code-conforming buildings, the options that are available to enhance performance, and the means by which an owner can determine the performance they need. Chapter 3 of this report provides guidance on assisting in the selection of appropriate performance objectives.

2.1.4 Code-Equivalent Design

One of the most common uses of performance-based seismic design is to demonstrate performance equivalent to prescriptively designed buildings, while not conforming to one or more of the prescriptive requirements in the building code.

Prescriptive code requirements are broad in nature and intended, to the extent possible, to address every conceivable building type or design consideration. A performance-based approach can allow engineers to omit certain prescriptive requirements, which is beneficial because it may result in designs that are less costly or have positive attributes that are not present in buildings that fully comply with prescriptive requirements. For example, current building codes require the use of special moment-resisting frames as part of the seismic force-resisting system for tall structures in regions of high seismicity. Placement of special moment-resisting frames around the building perimeter is not only costly, but also requires the presence of deep spandrel elements at the building facade. In recent years, many project development teams have used performance-based design procedures to justify the elimination of perimeter special moment-resisting frames in tall buildings, resulting in less costly buildings that also provide enhanced views, and therefore, greater marketability.

Alternative performance-based approaches also allow the use of innovative materials and systems. Because it often takes many code cycles before prescriptive building code requirements encompass new engineering and construction innovations, use of performance-based design to demonstrate equivalence allows the design and construction industry to move forward with innovative technologies as they become available.

2.2 Approval

Some buildings designed or upgraded using performance-based procedures will not meet prescriptive building code requirements. In most jurisdictions, it will be challenging to obtain a building permit if the design does not conform to applicable code requirements. However, building codes include provisions specifically intended to allow building permits for such designs to be issued.

2.2.1 Voluntary Seismic Upgrades

Many jurisdictions have adopted the 2015 *International Existing Building Code* (IEBC; ICC, 2015b) as the basis for regulation of existing buildings. 2015 IEBC Section 403.9 states:

> ***403.9 Voluntary seismic improvements***. *Alterations to existing structural elements or additions of new structural elements that are not otherwise required by this chapter and are initiated for the purpose of improving the performance of the seismic force-resisting system of an existing structure or the performance of seismic bracing or anchorage of existing nonstructural elements shall be permitted, provided that an engineering analysis is submitted demonstrating the following:*
>
> 1. *The altered structure and the altered nonstructural elements are no less conforming to the provisions of the International Building Code with respect to earthquake design than they were prior to the alteration.*
> 2. *New structural elements are detailed as required for new construction.*
> 3. *New or relocated nonstructural elements are detailed and connected to the existing or new structural elements as required for new construction.*
> 4. *The alterations do not create a structural irregularity as defined in ASCE 7 or make an existing structural irregularity more severe.*

The intent of this provision is to specifically permit voluntary, non-required seismic upgrades of buildings that do not fully conform to the requirements of the building code, if the engineer can demonstrate that the alteration work does not weaken the structure or make it more susceptible to earthquake damage. Although this broadly permits a wide range of voluntary seismic improvement programs, it does not specifically permit the use of new non-conforming construction as part of retrofit measures.

Some jurisdictions have not adopted the IEBC, and instead, enforce older editions of the *International Building Code* (IBC). Chapter 34 of IBC editions prior to 2015 presents language similar to that in IEBC Section 403.9.

2.2.2 Code-Conforming Designs

In many cases, buildings designed using performance-based seismic design procedures will conform to all applicable prescriptive requirements and may exceed some requirements. In such cases, it is only necessary to demonstrate compliance with the building code to obtain a building permit. It is not necessary to indicate or demonstrate that enhanced performance is desired or provided, nor is it necessary to reveal the procedures that were used to attain such performance.

2.2.3 Non-Conforming Designs

2015 *International Building Code* (ICC, 2015) provides the building official, and other authorities having jurisdiction, with broad latitude in issuing building permits to designs that knowingly do not comply with prescriptive code requirements in all respects, provided they determine that the design will perform as well as designs of similar buildings conforming to prescriptive requirements. 2015 IBC Section 104.11 states:

> ***104.11 Alternative materials, design and methods of construction and equipment.*** *The provisions of this code are not intended to prevent the installation of any material or to prohibit any design or method of construction not specifically prescribed by this code, provided that any such alternative has been approved. An alternative material, design or method of construction shall be approved where the building official finds that the proposed design is satisfactory and complies with the intent of the provisions of this code, and that the material, method or work offered is, for the purpose intended, not less than the equivalent of that prescribed in this code in quality, strength, effectiveness, fire resistance, durability and safety. When the alternative material, design or method of construction is not approved, the building official shall respond in writing, stating the reasons why the alternative was not approved.*

A building official has discretion in applying this clause. Even if a building official suggests that a performance-based approach may be used, the design team must still demonstrate to the satisfaction of the building official, and to the satisfaction of any other reviewers commissioned by the building official, that the design is equivalent. Historically, many, but not all, building officials have been willing to do this. Some have declined on the basis that they do not have the competency to determine if an alternative design is indeed equivalent, and are concerned that they may permit unsuitable construction. In such cases, a peer review process may help gain confidence in the use of alternative performance-based procedures.

2.3 Performance-Based Design Process

Figure 2-1 presents a flow chart for the performance-based design process. The following sections describe the steps in the process, and use of the FEMA P-58 methodology and tools for performance-based seismic design.

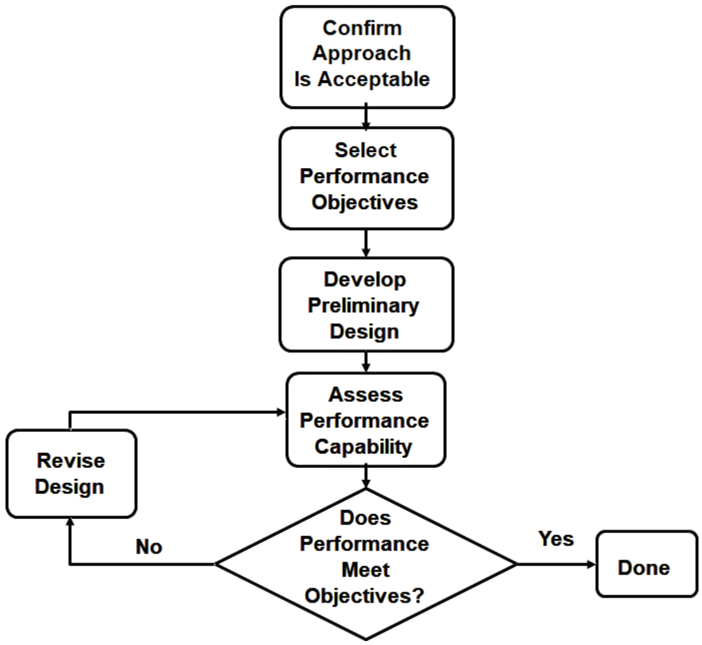


Figure 2-1 Performance-based seismic design process.

2.3.1 Confirm Approach

Prior to initiating a performance-based seismic design, it is essential to confirm that such an approach is acceptable to relevant stakeholders including the owner, the prime design professional, and the building official.

2.3.1.1 Owner

The owner or developer (with input from tenants, lenders, and insurers) is an integral part of the performance-based design process and needs to make the decision to engage in a performance-based design process. To make such a decision, the owner needs to understand that this is a choice, that such an approach may be beneficial, and that there may be associated risks. Some owners will be familiar with this process and may initiate discussion of performance-based approaches or specify that they be used. Other owners will require education before they are prepared to make such a decision. The structural engineer is typically the person most suited to assist an owner in becoming familiar with this approach. A companion publication to this report, FEMA P-58-7, *Building the Performance You Need*, *A Guide to State-of-the-Art Tools for Seismic Design and Assessment* (FEMA, 2018g) is designed to assist in providing such information. In addition, a quiz located at http://femap58.atcouncil.org/ can be used to quickly help an owner decide if they might be interested in a performance-based approach for their project.

Once an owner has expressed interest in a performance-based approach, they will need to select appropriate performance objectives.

2.3.1.2 Prime Design Professional

In cases where the structural engineer is not the prime design professional, it will be important to ensure that the prime design professional (e.g., architect) accepts the approach. This acceptance is important because use of performance-based design approaches can increase project risk. There is increased uncertainty regarding design measures that will be necessary to satisfy the building official and other reviewers to obtain a building permit. Even after successful permitting, there is increased risk should the building not perform as expected in an earthquake. Although the structural engineer would bear the primary responsibility for such risk, additional risk would also accrue to the architect. In addition, when performance-based design approaches are used, the level of engineering effort may be significantly increased, requiring larger fees and extended design schedules.

Once in agreement with the concept, the prime design professional can be a valuable partner in helping to educate the owner on the advantages of the approach, and assisting the owner in selecting appropriate performance objectives. The prime design professional can also help make sure that other design professionals contribute the assistance necessary to ensure that the resulting design meets the intended performance objectives. In the case of architects, it is essential that assistance is provided in designing architectural elements, such as ceilings, partitions, and cladding to minimize damage. In the case of mechanical or electrical engineers, it is essential that assistance is provided in adequately bracing and anchoring mechanical, electrical, and plumbing components.

2.3.1.3 Building Official

If the performance objectives selected by the owner are such that the building will comply with applicable prescriptive code requirements, possibly with some enhancements or informed selection of systems and detailing, the building official need not specifically approve the use of such an approach, or even be aware of it. In this case, the most expeditious path forward is simply to design and detail the structure in conformance with the code, with enhancements that may be appropriate to achieve the desired performance, and submit permit documents demonstrating code compliance. However, if the intent is to use performance-based methods to avoid compliance with certain prescriptive requirements, it is essential to obtain agreement with the building official that such an approach will be acceptable.

Before approaching the building official to determine if a performance-based design will be acceptable, it is necessary to have a sufficiently developed design approach to enable an explanation of the structural system, the selected performance objectives, and their equivalence to (or exceedance of) those prescribed by the building code, and the methods that will be used to demonstrate acceptable performance.

2.3.2 Select Performance Objectives

Performance objectives are quantitative statements of the desired building performance, for one or more potential earthquake shaking intensities, or scenarios, or over a period of time. One example of a performance objective is the basic performance goal underlying the design of all Risk Category II buildings under ASCE/SEI 7-10, *Minimum Design Loads for Buildings and Other Structures*, (ASCE, 2010) and ASCE/SEI 7-16, *Minimum Design Loads and Associated Criteria for Buildings and Other Structures*, (ASCE, 2017a). In these standards, there is a 10% (or lower) risk that a building will experience partial or total collapse, given that it experiences risk-targeted maximum considered earthquake (MCE_R) ground shaking, which is a scenario-based objective. In most regions of the country, because of the way MCE_R ground shaking intensity is determined, this equates to a 1% (or smaller) risk in 50 years that the building will experience earthquake-induced collapse, which is an example of a time-based objective. Performance inherent in the building code is both quantitative and expressed in probabilistic terms.

Although the building code is intended to achieve certain performance objectives, when design is conducted in accordance with the prescriptive requirements of the code, the actual performance capability of the design is rarely, if ever, explicitly evaluated. Instead, it is presumed that because the design complies with the prescriptive requirements, it can provide the performance expected of code-conforming buildings. Selection of performance objectives is fundamental to the performance-based design process, and engineers must explicitly demonstrate that the performance objectives can be achieved.

The owner is responsible for selecting the performance objectives.

The owner is responsible for selecting the performance objectives because these objectives have a direct impact on project cost and the building's performance over its life. However, the building owner does not have exclusive control over the objectives. Except in the case of voluntary seismic upgrade, the building official will typically insist, as a condition of issuing a building permit, that the design meets or exceeds the performance objectives inherent in the building code.

The owner will often require substantial assistance in selecting appropriate performance objectives. Building officials, although typically familiar with the life safety performance objectives inherent in the building code, do not typically consider performance objectives associated with repair cost, repair time, and other FEMA P-58 performance metrics. Chapter 3 provides additional guidance on assisting in the selection of performance objectives.

2.3.3 Develop Preliminary Design

The performance of a building in future earthquakes depends on many factors, including site conditions and seismicity; the structural system used for earthquake resistance, and its strength, stiffness, and configuration; and the type and location of nonstructural components, and how they are installed. Some of these factors can be controlled by the engineer and others cannot. Chapter 4 provides guidance on the selection of appropriate structural systems, and the strength and stiffness necessary, on average, to achieve desired performance for buildings of different occupancies. However, based on factors that are outside the control of the engineer, there can be considerable variation in the actual performance capability of the resulting building.

2.3.4 Assess Performance Capability

Before completing the design process and obtaining a building permit, it is necessary to demonstrate that the final building design can meet the selected performance objectives. FEMA P-58, Volume 1 (FEMA, 2018a) presents a methodology for assessing a building's performance once a design is sufficiently developed to permit meaningful detailed analysis. This methodology can be implemented using the *Performance Assessment Calculation Tool* (PACT), provided within FEMA P-58, Volume 3 (FEMA, 2018c) or other available proprietary software. Assessment of building performance using PACT, or other tools, will provide a quantitative measure of performance that can be compared to the selected performance objectives.

2.3.5 Iteratively Revise Design

Although the preliminary design procedures and tools provided herein are intended to result in designs that will, on average, achieve the desired performance, in some cases, when the actual performance capability is assessed, the design may not comply with the selected performance objectives. In such cases, it will be necessary to revise the design, re-assess performance, and iterate until the performance objectives are met. PACT provides data that can be used to guide the engineer in revising the design, including reports that indicate sources of poor performance (e.g., structural damage, curtain wall damage, interior partitions, ceilings). Most structural and nonstructural damage is directly related to the amount of story drift or floor acceleration that occurs at each level and in each direction. Informed by sources of poor performance, the engineer can modify the stiffness or strength of the structure to reduce the amount of story drift and floor acceleration, or specify components (or methods of installing components) that are less vulnerable to damage than those originally specified.

Once the design is revised, the engineer should reassess the performance capability of the building to ensure that the final design meets the selected performance objectives.

Chapter 3
Selecting Performance Objectives

The primary consideration in selecting performance objectives is the desire to control or limit the risk associated with one or more earthquake effects. This chapter describes the process for establishing and selecting appropriate performance objectives.

3.1 Overview

Seismic performance is a function of many factors, all of which are uncertain, including: ground shaking intensity, duration, spectral shape, building response, building contents, occupancy present during the earthquake, as well as post-earthquake actions taken by building officials, owners, design professionals and contractors. It is impossible to precisely predict the performance of a building in a future earthquake.

Performance objectives are quantitative statements of the acceptable risk of incurring consequences of different types, for different characterizations of earthquake hazard, and different levels of ground shaking intensity. Earthquake hazards can be characterized as a specific ground motion intensity, represented by an elastic acceleration response spectrum (used in intensity-based objectives), a specific earthquake magnitude on a known fault (used in scenario-based objectives), or the probabilistic consideration of all earthquakes that can occur in a period of time and the probability of occurrence of each (used in time-based objectives).

For new buildings and mandated seismic upgrades, performance objectives must, as a minimum, be equal to the performance underlying the building code or locally adopted retrofit ordinance. It is critically important to obtain agreement with the building official that the selected performance objectives are acceptable under the requirements of the building code. In voluntary seismic upgrades, or cases where better than code-equivalent performance is desired, the owner/developer should be the primary decision maker as to which performance objectives are adopted, sometimes with input from tenants, lenders, and insurers.

Often, the final selection of performance objectives is an iterative process that balances the cost associated with designing for a given performance against the benefits obtained. At the outset of the project, desired performance objectives are selected. As design decisions are made, the effects of the decisions are evaluated to verify that the final design is capable of achieving the desired performance.

3.2 Process for Establishing Performance Objectives

This section describes a recommended process for establishing and selecting performance objectives.

3.2.1 Assemble Stakeholders

Stakeholders who should be involved in the process include owners, developers, building officials, and prospective tenants, as well as structural engineers and other design professionals.

Important responsibilities of the structural engineer are to educate and guide the selection of objectives that can be considered for the given project, and to help ensure that the objectives being considered are reasonable and achievable. In almost all cases, this discussion should happen before the structural system is selected.

3.2.2 Determine Performance Measures of Interest

The selection of performance measures of interest for a given project will depend on the intended building use and specific concerns of a stakeholder, who may choose among measures related to safety, function, and cost. In many cases, setting a higher performance goal for one performance measure will lead to a design that provides higher performance in other measures, however, this is not always the case. Because losses are associated with both structural and nonstructural damage, performance measures must be expressed with consideration of the potential for both.

The following sections discuss performance measures considered in the FEMA P-58 methodology.

3.2.2.1 Casualties

Casualties include loss of life or serious injury requiring hospitalization, occurring within the building envelope. In FEMA P-58, this measure is reported as a casualty rate, the probability of any one occupant in a building becoming a casualty as a result of an earthquake.

ASCE/SEI 7-16 Tables 1.3-2 and 1.3-3 set target reliability values for structural stability in new structures designed with performance-based procedures. The values are dependent on the assigned Risk Category of the structure, and indicate the conditional probability of failure caused by Maximum Considered Earthquake (MCE_R) shaking hazard. Studies of the seismic performance of code-conforming buildings documented in FEMA P-58, Volume 5 confirm that for Risk Categories II and IV, the stated performance objectives result in a very low risk to life safety, which should be acceptable for most stakeholders and projects. Therefore, it is typically unnecessary to specify enhanced performance criteria for new buildings associated with structural collapse safety or failure of anchorage and bracing of nonstructural components.

Many existing buildings, however, will not provide the level of life safety protection expected of new buildings designed in accordance with ASCE/SEI 7-16. Therefore, protection of life safety is often a primary objective of seismic upgrade projects. Many stakeholders find it difficult to consider non-zero probabilities of injuring building occupants, and even more difficult to select appropriate levels of life safety as a basis for seismic upgrade. Although the FEMA P-58 methodology can indicate the probable number of earthquake-related casualties in a building, when life safety is a primary earthquake performance goal, it will typically be preferable for stakeholders to select a life safety goal that is closely related to the safety objectives inherent in ASCE/SEI 7-16 for new buildings.

The choice of an acceptable level of life safety protection will often be associated with the cost of achieving the selected goal, unless a locally adopted ordinance or building code requires otherwise. Examples of goals that may be selected for such projects include:

- Structural collapse, or nonstructural component attachment failure probabilities, similar to those specified in ASCE/SEI 7-16 for MCE_R shaking
- Structural collapse, or nonstructural component attachment failure probabilities, similar to those specified in ASCE/SEI 7-16, but for less intense earthquake shaking, such as Design Earthquake shaking or earthquake shaking with a 500-year recurrence interval

Because it is often very expensive and difficult to retrofit nonstructural components and systems, many retrofit projects will only consider the life safety effects of structural collapse.

3.2.2.2 Repair Cost

In the FEMA P-58 methodology, repair cost is defined as the cost, in present dollars, necessary to restore a building to its pre-earthquake condition, or in the case of total loss, to replace the building with a new structure of similar construction. In FEMA P-58, this measure is expressed as a percentage of the replacement value of the building. Repair costs represent only one aspect of potential financial loss due to earthquake damage. Other costs include loss of income due to business interruption during repair work, the cost to identify, plan, and permit repairs, and the cost of financing repairs.

Performance objectives associated with limiting repair costs represent enhanced objectives that are supplemental to those that underlie the basic design criteria in the building code. Nevertheless, maintaining expected repair costs at target levels can be an important performance objective for many buildings. One important driver for adopting performance objectives associated with repair cost is that many commercial mortgage lenders in regions of high seismicity consider probable repair costs when making decisions to offer financing on a property, as well as the terms of such financing. Many lenders base decisions on the assessed value of Scenario Expected Loss (SEL) for earthquake shaking having a 475-year mean return period. SEL represents a mean estimate of the repair cost, expressed as a fraction of building replacement value, given such shaking. Many lenders require an SEL value of 20% as a condition of making a loan. Some lenders also consider Scenario Upper Loss (SUL), which, for a given level of shaking, represents a repair cost, expressed as a fraction of replacement value, that has only a 10% chance of being exceeded. Acceptable SUL values vary considerably among lenders.

Most new buildings constructed in conformance with current building code requirements can provide SEL and SUL values typically deemed acceptable by lenders. However, many existing buildings will not achieve these values, and availability of financing is a frequent reason for selecting a performance objective with a lower repair cost when performing seismic upgrades.

3.2.2.3 Repair Time

In FEMA P-58, repair time is reported as the number of days required to restore a building to its pre-earthquake condition. Repair time is only a portion of the time needed to restore a building to its pre-earthquake condition. Additional time is required to identify, plan, and permit the work, arrange financing, and hire and mobilize contractors.

Most stakeholders are not specifically interested in repair time but are critically interested downtime, which is the time, following an earthquake, until a building can be safely restored to service. Downtime is an important design parameter for many building tenants, owners, and occupants. Loss of use of a building for an extended period of time following an earthquake can have severe impacts, including loss of ability to service customers, loss of revenue, and ultimately, loss of the survivability of the organization. Such issues are most significant to organizations that have large portions of their operations concentrated in a single facility, or multiple facilities in a region that could be severely affected by a single earthquake event. The amount of downtime that is acceptable to an organization will be highly dependent on the importance of the individual facility to overall operations, and the cost-benefit ratio associated with designing for reduced downtime.

The relationship between repair time and downtime is highly complex and dependent on the actions and capabilities of the building owner, occupant, and the community surrounding the building. Some occupancies are tolerant of repairs conducted while the building is in use, allowing for reduced downtime, relative to repair time, while other occupancies cannot tolerate ongoing repairs during building use. Some building operators have the financial resources to implement repairs without waiting for insurance reimbursement or loans, while others do not, resulting in potentially significant time before repairs can even initiate.

The FEMA P-58 methodology permits design for a target repair time rather than downtime because of the many factors affecting downtime that are outside of the control of the designer, and outside the influence of the individual building design. However, designing for targeted repair time can help an organization achieve targets for acceptable downtime.

3.2.2.4 Unsafe Placarding

An unsafe placard, determined in accordance with ATC-20 procedures (ATC, 2005) and posted on a building, is a post-earthquake safety determination that deems a building, or portion of a building, damaged to the point that entry, use, or occupancy poses immediate risk to safety. In FEMA P-58, this measure is expressed as the probability that a building will incur an unsafe placard following an earthquake, based on the occurrence of structural or nonstructural damage that is considered significant enough to trigger an unsafe posting.

When a building is posted as unsafe (i.e., red tag or placard) following an earthquake, this can substantially increase time-related impacts associated with the damage. When a building is posted unsafe, it can be difficult for design professionals and other to access the building to determine required repairs or retrieve contents. Therefore, stakeholders may elect to set performance objectives to minimize the risk that a building will incur an unsafe placard following an earthquake.

3.2.2.5 Building Repairability

The repairability measure is the probability that a building will be considered possible to repair following an earthquake. A repairable condition is one in which the building does not collapse, the permanent residual drift is less than 1%, and losses are less than of 50% of the building replacement cost. The inverse of this measure represents the risk that an earthquake will result in total loss of a building asset. Some stakeholders may wish to formulate objectives that maximize repairability, or minimize the inverse risk associated with irreparability.

3.2.2.6 Environmental Impacts

The FEMA P-58 methodology can quantify environmental impacts, in terms of embodied carbon and embodied energy, to restore a building to its pre-earthquake condition or, in the case of total loss, to replace the building with a new structure of similar construction.

Many buildings today are designed with the intent to minimize the carbon and energy embodiment, sometimes known as "net-zero" practices. Usually, such practices only consider energy and carbon impacts associated with building development and normal operations, neglecting repairs that may be needed in the event of an earthquake occur during the life of the building. When a building is damaged by an earthquake, repair efforts result in enlargement of the building's carbon footprint. By specifying seismic performance objectives associated with environmental impacts, stakeholders can ensure more comprehensive consideration of the likely impacts of their projects on the environment.

3.2.3 Define Earthquake Hazard

Performance objectives are defined by setting acceptable levels of damage and consequences based on earthquake ground shaking that may be experienced at the site. Other earthquake-related hazards, such as ground fault rupture, liquefaction, lateral spreading, land sliding, and tsunami inundation, are not measured in the FEMA P-58 methodology but should also be considered.

As part of the formation of performance objectives, stakeholders will need to select a hazard level for each performance measure, considering building code requirements and personal risk tolerance. In the selection of appropriate earthquake shaking intensities to couple with performance measures, a basic concept to note is that for a given site, larger events occur less frequently than smaller events. The probable performance of a building can be evaluated with different earthquake hazard characterizations based on the type of assessment:

- **Intensity-Based Assessments.** Intensity-based assessments evaluate the probable performance of a building conditioned on the occurrence of a specific intensity of motion, as represented by an elastic acceleration response spectrum. The basic life safety performance objective underlying the ASCE/SEI 7 seismic provisions (less than a 10% chance of collapse, given the occurrence of MCE_R shaking) is an example of the use of an intensity-based hazard representation in a performance objective. Commonly, the response spectrum represents a shaking intensity having a specified probability of exceedance in 50 years or may be a code-specified spectrum, such as the Design Earthquake or MCE_R. Such objectives are particularly useful for comparison with the performance expected of code-conforming buildings. Many stakeholders will want to form performance objectives using this type of an approach, often referring to the intensity as having a specific return period, e.g., 100 years, 500 years, or 1,000 years, because they have an intuitive understanding of decision making in this context.
- **Scenario-Based Assessments.** Scenario-based assessments evaluate the probable performance of a building assuming it is subjected to an earthquake scenario consisting of a specific magnitude earthquake occurring at a specific location relative to the building site. This hazard characterization will be useful in seismically active regions where historic earthquakes have occurred, or, where regional planners have forecast the likelihood of a specific magnitude earthquake on a specific fault. Examples include the San Francisco Bay Area, where stakeholders may wish to formulate objectives around a repeat of the 1906 earthquake, or an event on the Hayward fault, or the Seattle area, where stakeholders may wish to formulate objectives around occurrence of a large magnitude Cascadia subduction event.
- **Time-Based Assessments.** Time-based assessments evaluate the probable performance of a building considering all earthquakes that may occur, and the probability and probable consequences of each, to determine an average annual loss statistic for each performance measure. Time-based assessments can be used to specify limits on probable losses over a period of time, considering all earthquake sources that can affect a

site and the probability of occurrence of each potential event. This type of assessment is most useful for institutional investors or property owners with large portfolios, as well as for stakeholders using a cost-benefit approach to select performance objectives or to determine use of additional seismic protection, such as isolation or passive energy dissipation devices.

3.2.4 State Performance Objectives

Stakeholders will ultimately need to make a definitive statement as to the desired performance. In addition to indicating the desired limits on one or more earthquake consequences, and the earthquake hazard level for which consequences will be measured, it will also be necessary to state a level of confidence that the result will be achieved. The FEMA P-58 methodology forecasts earthquake performance in probabilistic terms, recognizing the uncertainties inherent in predicting actual earthquake outcomes. Stakeholders will need to determine their willingness to accept performance that is worse than specified. Stakeholders should be aware that when higher levels of confidence are desired, it may take substantially more protective design measures, and increased construction costs, to achieve the specified performance at the desired level of confidence.

3.2.5 Iterate on Performance Objectives

In some cases, stakeholders may be able to make a final selection of performance objectives based on the steps above, but final selection is normally an iterative process. Iteration is largely due to the need to assess the feasibility and practicality of selected performance objectives in the context of other project considerations, such as cost and schedule, and the need to be integrated into architectural, mechanical, and electrical design concepts.

3.3 Using Performance Objectives in FEMA P-58

The selection of performance measures combined with the consideration of earthquake hazard will lead to a decision regarding how the objective is framed, which will lead to the choice of a FEMA P-58 assessment type. For example, an intensity-based objective for an emergency operations center may be stated in terms of the median estimated repair time in the event of an earthquake having a 10% probability of occurrence in 50 years. Alternatively, consequences may be stated in terms of the repair time resulting from the occurrence of a scenario event, or they may be time-based.

3.3.1 Intensity-based Performance Objectives

Intensity-based performance objectives are framed as statements of acceptable measures resulting from specific intensities of ground shaking. Any of the performance measures discussed in Section 3.2 may be addressed in an intensity-based objective.

Figure 3-1 shows an example of the variation in median loss in terms of percentage of replacement cost for a hypothetical building with a given lateral strength and stiffness as a function of increasing earthquake intensity, represented as a percentage of MCE shaking. The same figure could have been shown with intensity represented in terms of return period. As intensity increases, median loss will increase, though not on a linear basis.

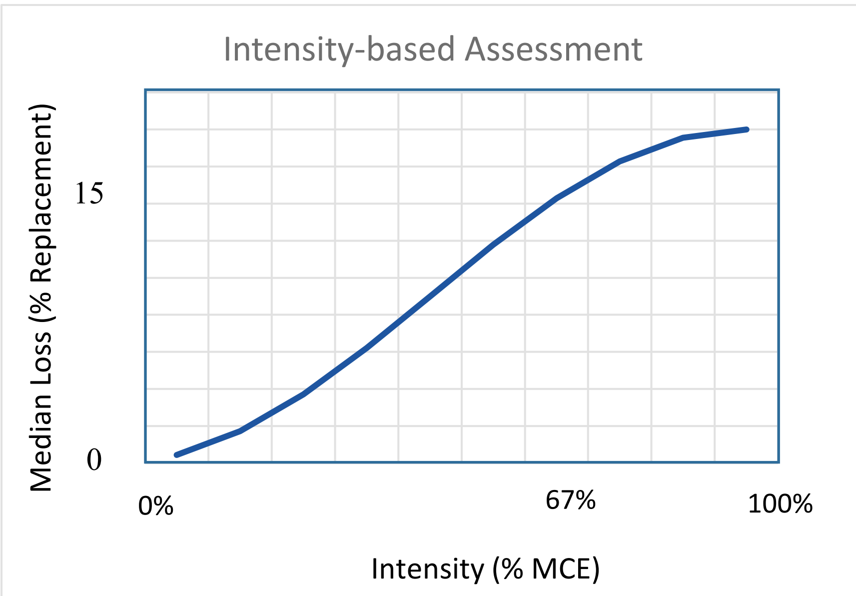


Figure 3-1 Example result of an intensity-based assessment.

Typical intensity-based objectives are conditioned on a single intensity, selected to relate to tangible risk levels for the performance measure of interest. For example, "if ground-shaking equivalent to two-thirds of MCE ground motion occurs, median repair costs should not exceed 20% of the building replacement value, there should be negligible probability of casualties, and median repair time should not exceed 30 days."

Performance objectives can include one or more performance measures at one or more intensity levels.

Stakeholders concerned with consequences related to business interruption may be interested in performance objectives related to functionality associated with multiple levels of probability of occurrence, and may include one or more performance measures at one or more intensity levels. For example, objectives could consider a frequent event, such as one having a 50% probability of exceedance in 50 years (72-year return period), and a larger event having a 10% probability of exceedance in 50 years (475-year return period).

Life safety related performance measures are commonly considered at the earthquake intensity associated with the building code design earthquake level, since the primary purpose of the code is protection of life safety. For example, an objective of interest may be the probability of casualties occurring at an intensity level corresponding to two-thirds of MCE level shaking.

3.3.2 Scenario-based Performance Objectives

Scenario-based performance objectives are framed as statements of acceptable risk of casualties, repair costs, and repair time resulting from the occurrence of the scenario event. An example of a scenario-based performance objective is a statement that if a magnitude-7.0 earthquake occurs on the San Andreas Fault, median repair costs should not exceed 15% of the building replacement cost, there should be no casualties, and repair time should not exceed two months.

Performance objectives may include multiple scenarios, depending on the site location relative to known faults in the region. For example, if a site is located two miles from a fault capable of a magnitude-7.0 earthquake, and 10 miles from a fault capable of a magnitude-6.5 earthquake, these scenario events may be used to describe two performance objectives, one major and one moderate. Each scenario could be associated with the same or different performance measure, and each would be associated with different performance objectives conditioned on the two scenarios. For example, one objective could be for the building to achieve no more than a 20% probability of incurring an unsafe placard in the major scenario earthquake, and a second objective could be for the building to achieve no more than a 10% probability of incurring an unsafe placard in the moderate scenario earthquake.

3.3.3 Time-based Performance Objectives

Time-based assessments can be used to specify limits on probable losses over a period of time, considering all earthquake sources that can affect a site and the probability of occurrence of each event. The impact most commonly considered in time-based assessments is loss associated with repair cost, which may be considered in terms of the average annual loss, or the loss over a specific interval of time, such as 50 or 100 years.

Time-based performance objectives are particularly useful when using cost-benefit analysis to determine performance. If the average annual repair cost over the building life is known, it is possible, using engineering economics, to determine the net present value of probable repair costs over the building's useful life, using the formula:

$$NPV = \frac{(AAL)}{i}\left(1 - \frac{1}{(1+i)^N}\right) \tag{3-1}$$

where *NPV* is the net present value of the future losses in dollars, *i* is the time value of money, or interest rate, *AAL* is the average annual loss in dollars, and *N* is the building or investment lifetime in years. Increased investment in seismic protection will reduce the size of average annual losses, *AAL*, resulting in a lower net present value, *NPV*. The optimum investment would be a level at which a dollar of additional investment in earthquake protection has a probable return of more than one dollar in future losses avoided.

3.3.4 Confidence Level

Confidence level reflects the desired certainty that the actual earthquake performance of a building will be at least as good, or possibly better than a target level. The following levels are commonly used:

- **Median.** The median value of a performance measure represents that value which will be exceeded half the time. There is a 50% chance that actual performance will be better than or equal to the median level.
- **Mean.** The mean value is the average or expected outcome. Since distributions of performance measures tend to be skewed, the mean value is usually larger than the median value. Typically, there is a 40% chance that a mean value will be exceeded.
- **90^{th} Percentile.** The 90^{th} percentile value represents the worst performance in 9 out of 10 similar buildings. There is a 10% chance the 90^{th} percentile value will be exceeded.

Figure 3-2 illustrates the probability density function for repair cost for a hypothetical building illustrating the median (10% of replacement value), mean (11% of replacement value), and 90^{th} percentile (17% of replacement value). Figure 3-3 shows the same distribution in the form of a cumulative probability distribution.

The choice of confidence level depends on a stakeholder's need for certainty in results. For example, stakeholders considering the expected performance of an emergency operations center or critical manufacturing facility may choose the 90^{th} percentile confidence level for post-earthquake repair time or avoidance of unsafe placarding. Owners of a large campus of buildings may find use of mean repair costs to be an appropriate level of confidence because when aggregated over all buildings, this best expresses the probable value of the loss.

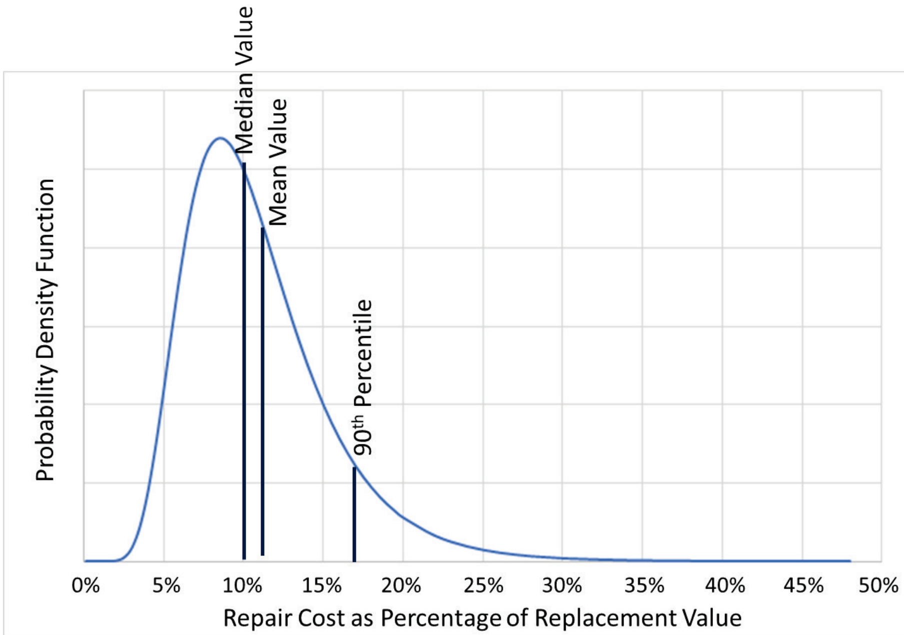


Figure 3-2 Probability density function for repair cost illustrating median, mean, and 90th percentile values.

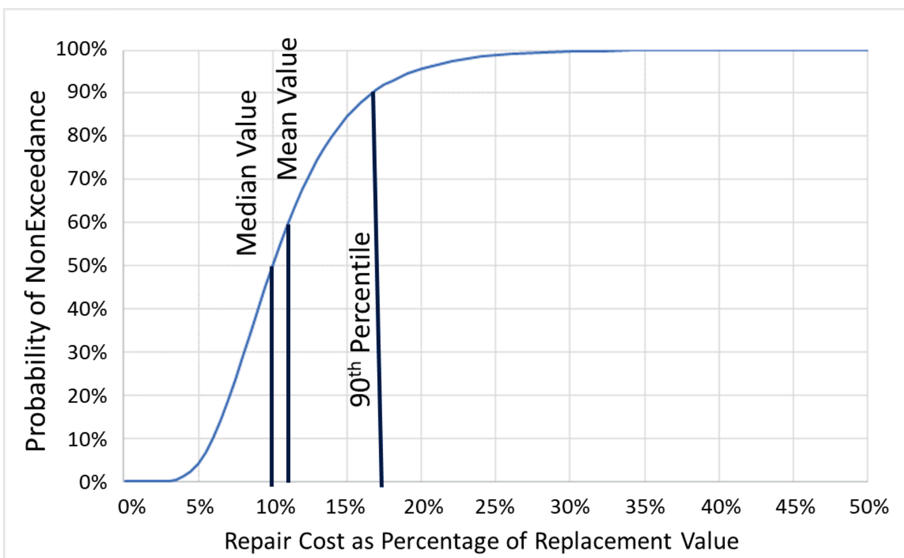


Figure 3-3 Cumulative probability distribution for repair cost illustrating median, mean, and 90th percentile values.

3.4 Other Performance Considerations

3.4.1 Utilities and Back-up Systems

Most buildings depend on the availability of electrical power, water, and other utilities to be useful for their intended occupancy. Earthquakes can cause disruption of utilities, which affects recovery planning. For buildings in which post-earthquake operations are critical, whether for societal or financial reasons, owners can consider arranging in advance for back-up systems to provide fuel, water, power, and wastewater storage. Replacement equipment or parts may be stored on-site, or locally off-site, or arrangements can be made in advance for their replacement, if needed. In complex laboratory and manufacturing operations, the storage of work-in-process and inventory may be appropriate.

3.4.2 Redundancy

Redundancy is an important consideration in establishing performance objectives, particularly for buildings supporting operations that are critical, either to society or a private entity. Setting performance objectives should account for the availability of facilities that have redundant or overlapping functions. For example, the need for all hospitals in a region to operate continuously after an earthquake varies regionally. Stakeholders considering performance objectives associated with a substantial initial investment may choose to consider the availability of other similar facilities located nearby, or outside the region affected by the earthquake.

Redundancy is also a major consideration for laboratory and manufacturing facilities. Higher performance objectives, and the associated costs, may be appropriate for laboratory buildings that house unique research activities, or factories that produce a component that is not easily obtained elsewhere.

3.4.3 Real Estate Industry Guidelines

The real estate industry in regions of high seismicity follow selected procedures to determine the financial viability of a project, and these considerations may influence the selection of performance objectives.

3.4.3.1 Probable Maximum Loss

Lenders, loan servicers, insurers, and equity investors use a measure of seismic risk known as Probable Maximum Loss (PML). Building owners and other stakeholders may also use this measure to make decisions related to property investment, including the purchase of earthquake insurance. In many cases, investment and insurance decisions are based on a PML threshold value, such as 20%.

ASTM E-2026, *Standard Guide for Seismic Risk Assessment of Buildings*, (ASTM, 2016a) and ASTM E-2557, *Standard Practice for Probable Maximum Loss (PML) Evaluations for Earthquake Due-Diligence Assessments*, (ASTM, 2016b) set standard procedures for seismic evaluations and the development of PMLs for use in the financial industry. These standards define several different measures including:

- **Scenario Expected Loss (SEL).** This represents the mean repair cost, expressed as a percentage of building replacement value, for a selected intensity of ground motion.
- **Scenario Upper Loss (SUL).** This represents the 90^{th} percentile repair cost, expressed as a percentage of building replacement value, for a particular intensity of ground motion.
- **Probable Loss (PL).** This represents the loss having a specific probability of exceedance over a specified number of years.

Scenario Expected Loss and Scenario Upper Loss can be determined by performing intensity-based assessments; Probable Loss from time-based assessments.

The SEL and SUL loss measures commonly reflect damage statistics for 475-year return period shaking, while PL values correspond to ground motions occurring over a specified timeframe, but not a specific scenario event. Both SEL and SUL can be determined by performing intensity-based assessments for response spectra having a specified return period. The SEL is obtained by computing the mean repair cost and the SUL is determined directly from the performance curve cost at the 90^{th} percentile. PL can be derived from a time-based assessment using an appropriate return period for the assessment.

3.4.3.2 U.S. Resiliency Council Rating System

Some stakeholders may elect to design buildings to achieve a specific rating in accordance with the U.S. Resiliency Council (USRC) rating system. This system identifies the expected performance of buildings in earthquakes across three performance categories: Safety, Damage, and Recovery. USRC ratings address structural and nonstructural systems and are applicable to both new and existing buildings. The ratings are based on median performance in the 475-year return period ground motion and assign one to five stars in each of the three categories. Table 3-1 shows the USRC performance goals.

Each of the USRC ratings can be assessed using the FEMA P-58 methodology. On a preliminary basis, Safety can be assessed based on casualties, or it may be assessed using the ASCE/SEI 41 methodology. The final safety determination should be made based on analysis conducted utilizing the *Performance Assessment Calculation Tool* (PACT), considering collapse in the 475-year ground motion. The USRC assesses damage based on the mean estimated loss, and recovery based on median repair time. It is noted that PACT results for loss would be indicated as mean results, not median.

Table 3-1 U.S. Resiliency Council Rating System Performance Goals

USRC Rating Range for a New Code-Compliant Building (Depends on Structural System)					
Safety		**Damage**		**Recovery**	
5★	Blocking of exit paths unlikely	5★	Minimal damage (<5%)	5★	Immediately to days
4★	Serious injuries unlikely	4★	Moderate damage (<10%)	4★	Within days to weeks
3★	Loss of life unlikely	3★	Significant damage (<20%)	3★	Within weeks to months
2★	Isolated loss of life	2★	Substantial damage (<40%)	2★	Within months to a year
1★	Loss of life likely	1★	Severe damage (40%+)	1★	More than one year

3.5 Expected Performance of Code-Conforming Buildings

The expected performance of buildings designed to the minimum prescriptive requirements of the building code can be an important measure for selecting performance objectives, or even deciding to adopt a performance-based approach. FEMA P-58, Volume 5 presents findings from studies conducted to determine the expected performance of code-conforming buildings. Results from these studies can be used to determine if code performance is acceptable for a given project, or to inform the selection of project-specific performance objectives.

The FEMA P-58 methodology was used to assess a wide range of buildings and systems meeting ASCE/SEI 7-10 structural and nonstructural seismic design requirements in regions of high seismicity. The following structural systems were considered: steel special moment-resisting frames (Steel SMRF), reinforced concrete special moment-resisting frames (RC SMRF), steel buckling-restrained braced frames (BRBF), steel special concentrically-braced frames (SCBF), and special reinforced concrete shear walls (Special RCSW).

Archetypical representations of buildings with a variety of code-conforming characteristics were used. Archetypes were defined by lateral system type, height, lateral strength, lateral stiffness, occupancy, and design ground motion. A total of 1,755 archetypes were designed for five different seismic force-resisting systems, two Risk Categories (RC II and RC IV), three levels of seismic hazard (Low SDC D, SDC D, and SDC E/F), three height variants (low-, mid-, and high-rise), and two occupancies (office and healthcare).

The concept of a code-conforming design space was developed to bound the range of possible archetype designs. The design space is intended to represent a reasonable range of lateral strengths and stiffnesses that would be expected in typical modern buildings designed in accordance with ASCE/SEI 7-10.

The FEMA P-58 assessment of code-conforming buildings showed that performance varies significantly across the range of code-complying systems, and that structural and nonstructural design decisions can have a measurable impact on the resulting performance. Thus, by selecting an appropriate structural system, and proportioning it with sufficient strength and stiffness, an engineer can do much to control a building's probable seismic performance. Although traditional code performance expectations focus on safety, current design requirements were also shown to provide some measure of protection of property.

Table 3-2 presents generalized performance expectations for code-conforming buildings from FEMA P-58, Volume 5, developed based on: performance assessment results averaged across all points in the design space for each system; experience in post-earthquake damage investigations and subsequent repairs; and engineering judgement. Generalized performance has been evaluated for two earthquake levels: the design level earthquake and the Maximum Considered Earthquake (MCE). The design and MCE earthquake levels are based on ASCE/SEI 7-10 ground motion values, with design earthquake shaking taken as two-thirds of MCE shaking.

In the table, repair costs are expressed as a percentage of the replacement value of the building. Repair time is expressed in days. Casualty rates are expressed as the probability, in percent, of any one occupant in a building becoming a casualty as a result of an earthquake. The probability that a building will be posted unsafe is shown, as is the probability that the building will be considered possible to repair following an earthquake. More detailed information is available in FEMA P-58, Volume 5, including the performance of individual structural systems, and for other levels of shaking intensity.

Generalized performance expectations in FEMA P-58, Volume 5 are presented based on median values of loss. If higher levels of confidence are desired, 90th percentile values of these performance measures can be approximated by doubling the median values reported in the table.

Table 3-2 Generalized Performance Expectations for Code-Conforming Buildings (FEMA P-58, Volume 5, Table 6-1)

Performance Measure	Performance Expectation	
	Design EQ	MCE
Risk Category II – Office		
Repair Cost	10%	30%
Repair Time	45 days	150 days
Casualty Rate	1.0%	2.0%
Probability of Unsafe Placard	20%	40%
Repairability	95%	80%
Risk Category II – Healthcare (Medical Office Building or Laboratory)		
Repair Cost	20%	40%
Repair Time	60 days	180 days
Casualty Rate	1.0%	2.0%
Probability of Unsafe Placard	20%	40%
Repairability	85%	65%
Risk Category IV – Office (Emergency Operations Center)		
Repair Cost	5%	15%
Repair Time	30 days	75 days
Casualty Rate	0.5%	1.5%
Probability of Unsafe Placard	10%	25%
Repairability	98%	90%
Risk Category IV – Healthcare (Hospital)		
Repair Cost	10%	20%
Repair Time	45 days	100 days
Casualty Rate	0.5%	1.5%
Probability of Unsafe Placard	10%	25%
Repairability	95%	85%

Chapter 4
Developing Preliminary and Final Designs

The performance-based seismic design process includes selection of a structural system, development of a preliminary design, and assessment of its performance capability. Preliminary designs are iteratively revised, considering factors affecting performance, and a final design that meets the performance objectives is ultimately developed. This chapter presents two approaches for developing preliminary designs along with considerations for developing final designs.

4.1 Overview of Preliminary Design

Preliminary design is initiated with the selection of a candidate structural system and consideration of structural design factors. The strength and stiffness of the system are determined based on code compliance and performance capability. Once the required strength and stiffness are known, the structural layout, number, and required size of structural components are determined. In design iteration, other factors, such as building configuration and nonstructural component contributions to loss, are also considered.

This chapter presents the following two approaches for preliminary seismic design:

- **General procedure.** The general procedure is applicable to any structure. It requires iterative performance assessments evaluating performance for varying design assumptions. This approach, along with simplifying approximations, is described in Section 4.3.
- **Direct design procedure.** The direct design procedure is limited to buildings with selected systems (e.g., buckling-restrained braced frame, steel concentrically braced frame, steel special moment frame, reinforced concrete shear wall, and reinforced concrete special moment frame), occupancies (office or healthcare), and Risk Categories II or IV. The *Performance Estimation Tool* (PET), provided in FEMA P-58, Volume 3, is used to directly evaluate the effects of varying assumptions on performance, and to directly determine the strength and stiffness required to meet selected performance objectives. This approach, along with

recommendations for extrapolating beyond limitations in available data, is described in Section 4.4.

4.2 Structural Design Factors Affecting Performance

Once performance objectives for a project have been selected, and a preliminary architectural layout has been determined, structural design factors affecting building performance should be considered.

4.2.1 System Selection

All of the structural systems listed in ASCE/SEI 7-16, Table 12.2-1 are presumed capable of providing minimum acceptable seismic performance when designed in accordance with prescriptive requirements; however, the performance capability of these systems in terms of FEMA P-58 performance metrics will vary considerably. Some systems are flexible, permitting large story drifts that can damage architectural and other nonstructural components. Other systems are strong, transmitting large floor accelerations that can damage contents. Some systems are susceptible to developing large permanent drift, rendering them difficult, and potentially impossible, to repair. Some structural systems include components that can be easily repaired or replaced, while other systems are expected to incur damage that may be difficult to repair.

Although seismic performance capability is an important factor to consider in the selection of a structural system, it is not the only factor. In addition to seismic performance capability, the most appropriate structural system should be selected considering:

- Compatibility with the required story height and architectural layout
- Ability to meet the desired performance objectives, project cost, project schedule
- Availability of required materials and construction expertise at site location
- Inherent fire resistance
- Floor vibration characteristics

Some systems offer advantages for buildings of a certain size and occupancy, and are, therefore, most commonly selected for certain building types. For example: wood light-frame or cold-formed steel frame systems are commonly used in low- to mid-rise residential construction; steel frame systems are common in mid- to high-rise office construction; and reinforced concrete systems are often used in mid- to high-rise residential construction.

4.2.2 Stiffness and Strength

The building code specifies the minimum required strength for new buildings as a function of site seismicity, soil class, occupancy category, and structural system. Indirect requirements are placed on building stiffness through the specification of maximum permissible story drift ratio when subjected to code-specified minimum seismic design forces. However, there are no limitations on design of buildings with additional stiffness and strength. Engineers are at liberty to increase the stiffness and strength of buildings beyond code-specified minimum values.

Increasing the stiffness of a system reduces the amount of lateral drift that a building will experience when subjected to earthquake shaking, resulting in reduced damage to components that are sensitive to drift, such as cladding and partitions. However, increasing building stiffness reduces the fundamental period of the structure, resulting in increased acceleration and strength demands, which can lead to damage in components that are force-controlled or sensitive to acceleration, such as mechanical and electrical components and tenant contents.

Increasing the strength of a system reduces the potential for yielding, decreases ductility demands, and reduces potential structural damage and residual drift. However, increasing strength makes it possible for the building to transmit increased accelerations throughout the structure, increasing the potential for damage to acceleration-sensitive components.

Achieving targeted performance will require a balance between selected values of stiffness and strength. Sections 4.3 and 4.4 provide procedures for determining stiffness and strength that will achieve the selected performance objectives.

4.2.3 Supplemental Protective Systems

Supplemental protective systems can be considered for enhancing the seismic performance capability of a system in order to achieve selected performance objectives. The two most common technologies used for this purpose are seismic isolation and energy dissipation (i.e., damping) systems. Sometimes, it is advantageous to employ both technologies in achieving higher performance objectives.

Seismic isolation improves performance by: lengthening the fundamental period to reduce accelerations experienced by the structure, adding hysteretic damping to reduce the response of the structure, and providing a ductile interface between the structure and the ground that is capable of resisting large displacements with minimal input to the structure. Properly designed seismic isolation systems can enable structures to withstand intense ground shaking with minimal damage and consequence. Seismic isolation is most compatible in buildings with stiff structural systems, such as reinforced concrete or masonry shear walls and steel braced frames. To ensure proper function of the isolation system, the structure above the isolation plane must be designed for essentially elastic behavior under design shaking.

Seismic isolation systems are most effective when used in a structural system with a fixed base fundamental period of 1 second or less. ASCE/SEI 7-16 Chapter 17 provides seismic design requirements for new seismically isolated buildings, and ASCE/SEI 41-17 Chapter 14 provides criteria for seismic isolation of existing buildings.

Damping systems improve performance by dissipating earthquake energy through conversion of kinetic energy to heat energy in components (i.e., dampers) that are specifically designed for this purpose. As a result of damping, lateral displacement response is reduced, resulting in less damage to structural components and drift-sensitive nonstructural components. Because the amount of energy dissipated is related to displacement in the dampers, damping systems are most effective in relatively flexible structural systems, such as moment frames. For damping systems to be effective, it is typically necessary that the structure experience only limited inelastic behavior.

Damping systems are most effective when used in a structure with a fundamental period of vibration of 1 second or more. ASCE/SEI 7-16 Chapter 18 provides seismic design requirements for new buildings with damping systems, and ASCE/SEI 41-17 Chapter 14 provides criteria utilizing damping systems in existing buildings.

4.3 General Procedure for Preliminary Design

The general procedure is initiated by designing a building to conform to applicable building code requirements, potentially with some enhancement or modification. The preliminary design is then subjected to a performance evaluation using the FEMA P-58 methodology, and the predicted performance is compared with targeted performance objectives. If the predicted performance fails to meet the targeted performance, the design is revised through one or more of the following actions: changing the building configuration, strengthening the design, stiffening the design, or selecting less fragile (i.e., more robust) components. The revised design is then reassessed to evaluate performance in an iterative process until the design satisfies the targeted performance objectives.

The general procedure involves assembling a building performance model to a level of detail that is appropriate for the current stage of design, along with estimates of stiffness and strength, and approximate estimates of earthquake demands for input into the *Performance Assessment Calculation Tool* (PACT), or other comparable tool, to estimate building performance. PACT results provide estimates of the probable distribution of repair cost, repair time, and other earthquake impacts, as well as information on components and systems that significantly contribute to losses. With this information, preliminary designs can be effectively revised to achieve the targeted performance.

The following sections describe approximations and shortcuts available for use in a preliminary design context in conjunction with detailed procedures outlined in FEMA P-58, Volume 1 (*Methodology*) and illustrated in Volume 2 (*Implementation Guide*). Approximations and shortcuts are provided to reduce the level of effort associated with analyses of buildings utilizing conventional structural systems such as shear walls, moment frames, and braced frames, as well as structures utilizing protective technologies, such as seismic isolation and damping systems.

4.3.1 Preliminary Building Performance Model

A building performance model is a quantified description of the building including structural and nonstructural components that have susceptibility (fragility) to earthquake-induced damage, as well as the population (i.e., number of persons) likely to be present in the building at different times. Building components and systems can generally be categorized as architectural components, structural components, mechanical/electrical/plumbing components, and contents.

4.3.1.1 Architectural Components

The following architectural components are considered the most significant contributors to consequences (i.e., losses) experienced by buildings in earthquakes:

- Exterior cladding
- Ceilings
- Partitions
- Stairways

> **Short Cut for Preliminary Design**
> It is considered adequate to include only the following architectural components in a preliminary building performance model: Exterior cladding, ceilings, partitions, stairways, and elevators.

- Elevators

Accordingly, for purposes of preliminary design, it is considered adequate to include only these components in the building performance model for preliminary design.

To the extent that preliminary architectural drawings define the quantities of these components, they should be used directly to define the building performance model. Where they are not defined, the *Normative Quantity Estimation Tool* provided in FEMA P-58, Volume 3 can be used to define approximate quantities based on number of stories, floor area of each story, building occupancy, and square footage. Once the quantity for each of the architectural components is defined, it will be necessary to associate a fragility specification with each component type.

FEMA P-58, Volume 3 includes a *Fragility Database* with specifications for many architectural components. Fragility specifications associated with the building Seismic Design Category should be selected. The following should also be considered when specifying architectural components:

- The *Fragility Database* provides specifications for several different types of exterior cladding including glazed storefronts, glazed curtain walls, and precast panels. Some fragility specifications require that the engineer input the median deformation demand at which damage states will initiate. For preliminary design, use of fragilities computed from code-required design earthquake displacement capacity for cladding in accordance with the procedures of FEMA P-58, Volume 2, is recommended.
- Hard ceilings constructed of plaster or gypsum board on suspended framing are considered rugged in the *Fragility Database* and need not be included in the performance model. Fragility specifications for suspended lay-in acoustic tile ceilings are provided in the *Fragility Database*.
- Damage to partitions can be a significant contributor to losses in buildings with flexible seismic force-resisting systems, even in moderate levels of shaking. At modest levels of story drift, damage consists of cracking of gypsum board sheathing, concentrated primarily at re-entrant corners, above door and window openings, and at wall intersections. At larger story drifts, steel stud framing can become permanently deformed requiring replacement of the entire wall. Full-height walls, that frame between floor levels are more susceptible to damage than partial height walls. Full-height walls are typically used as code-required fire barriers

and are typically used to enclose stairwells, elevator and air shafts, and corridors required for egress. Full-height walls are also commonly used around lavatories to limit sound and odor migration. Most other partitions are partial height. There are two types of partial-height walls: (1) those in which the framing and sheathing terminate at the ceiling level; and (2) those in which the framing extends to the floor level above, but the sheathing stops at the ceiling level. Both types have substantial resistance to earthquake-related damage. The *Fragility Database* includes fragilities for full-height walls with several types of detailing including walls with the framing hard-attached to the floor above and walls with compensation channels that allow sliding of the wall relative to the floor above. Detailing with compensation channels is recommended. The building performance model should include selection of fragility specifications representing the detailing that will be used in the building.

- Several options for stairway systems are provided in the *Fragility Database*. Unless it is known that an alternate type of stair will be used, steel stringers with provision for displacement equal to the code-specified drift limit can be assumed for preliminary design.
- Separate fragility specifications are provided for traction and hydraulic elevators in the *Fragility Database*. Most elevators that service three stories or less will be hydraulic. Traction elevators should be assumed in applications servicing more than three stories.

4.3.1.2 Mechanical/Electrical/Plumbing Components

If the mechanical/electrical/plumbing (MEP) systems are not design-build, the structural engineer should coordinate with mechanical, electrical, and plumbing design professionals to identify the size and types of equipment and systems that will be specified. Important MEP components that are the most significant contributors to consequences (i.e., loss) include:

- Air handlers
- Chillers
- Generators
- Fire sprinkler drops
- Domestic water piping
- Packaged air conditioning systems

The *Normative Quantity Estimation Tool* provides recommendations for the quantity and size of typical MEP components and systems. The *Fragility*

Short Cut for Preliminary Design
The key fragility for MEP equipment is anchorage.

Database presents fragility specifications for these components. The key fragility for MEP equipment is the adequacy of anchorage. FEMA P-58, Volumes 1 and 2 present procedures for computing fragilities for equipment anchorage based on code-specified minimum capacity.

Electrical panels, transformers, motor control centers, and switchgear do not typically have a large impact on seismic performance and can be ignored for preliminary design.

4.3.1.3 Contents

Damage to contents can dominate the consequences of earthquake shaking on buildings, particularly for moderate levels of motion. However, the effect of contents on performance is not necessarily of interest to all parties. Owners of multi-tenant office buildings and residences may not be concerned about content performance because they do not own the contents, nor are they responsible for replacement of contents when damaged. However, the performance of contents can be a critical concern for operators of certain types of buildings, including most structures designated as essential facilities (Risk Category IV), laboratory, research, and manufacturing facilities.

Short Cut for Preliminary Design
FEMA P-58, Volume 3 provides fragility specifications for common contents in office and residential occupancies.

The *Fragility Database* includes fragility specifications for common contents found in office and residential occupancies. It does not include fragility specifications for Risk Category IV, laboratory, research, and manufacturing facilities. Suppliers of critical equipment may have some fragility data available. If the performance of contents is critical to achieving the targeted performance objectives, consideration should be given to specifying shake table qualification testing as part of purchase specifications for the equipment.

Most vulnerable equipment and contents in laboratory, healthcare, and manufacturing facilities include unanchored countertop items or cart-mounted items. FEMA P-58, Volumes 1 and 2 provide procedures for estimating the fragility of these items for sliding or overturning, including examples illustrating implementation of these procedures.

When properly anchored or secured, many contents are relatively rugged. FEMA P-58, Volumes 1 and 2 provide guidance for developing fragilities for equipment anchorage. The consequences of anchor failure will be largely dependent on the type of equipment and the types of connections (e.g., electrical and gas) to the surrounding facility. Engineers developing fragilities for such items will need to work with equipment suppliers, or persons knowledgeable in the use of the equipment, to develop an understanding of the likely consequences of failure in terms of repair cost, repair time, and other impacts.

4.3.1.4 Structural Components

The *Fragility Database* provide a large number structural fragility specifications covering most structural systems, including structural components that conform to current code detailing provisions, and those that do not. Structural information necessary to develop a building performance model for preliminary design is similar to the level of information presented in typical conceptual and schematic structural documents, including:

- Identification of the structural system (e.g., steel concentric braced frame, masonry wall, light framed wall)
- Identification of the number and dimensions of bays of walls, moment frames, or braces to be used in the structure
- Identification of approximate framing sizing, including approximate wall thickness, approximate member depth, and weight
- Level of seismic detailing (e.g., special, intermediate, ordinary, non-conforming) to be used

With this information, the engineer can enter structural components into the building performance model using the standard fragility specifications available in PACT, and choose fragility specifications appropriate to the design concept in accordance with the instructions in FEMA P-58, Volumes 1 and 2.

4.3.1.5 Collapse Fragility

PACT also requires input of a building-specific collapse fragility. For new, code-conforming structures, the simplified method contained in FEMA P-58, Volume 1 should be used to estimate collapse fragility based on the response modification factor, R, and overstrength, Ω_0, values appropriate to the selected structural system. For existing buildings, the results of an approximate pushover analysis can be used together with the *SPO2IDA* tool provided in FEMA P-58, Volume 3 to develop a collapse fragility. For preliminary design, it is typically sufficient to assume that only a single collapse mode occurs, encompassing complete collapse of the structure. More refined collapse modes can be considered, if desired.

Short Cut for Preliminary Design

The collapse fragility of new structures can be determined with the simplified method of FEMA P-58, Volume 1.

4.3.1.6 Population Model

Short Cut for Preliminary Design
An equivalent continuous occupancy (ECO) model can be used to estimate population.

As described in FEMA P-58, Volume 1, PACT has built-in population models for commercial office, education, healthcare, hospitality, multi-unit residential, research laboratory, retail, and warehouse occupancies. For preliminary design, it is typically acceptable to use an equivalent continuous occupancy (ECO) model, which is a time-weighted average of the population theoretically occupying the building on a continual basis.

4.3.2 Demand Estimation for Conventional Structures

Short Cut for Preliminary Design
Preliminary performance assessment should be conducted with the simplified analysis procedure of FEMA P-58, Volume 1 in each primary direction of building response.

The FEMA P-58 methodology allows both nonlinear dynamic analysis and simplified analysis procedures. For preliminary design, the level of rigor and effort associated with nonlinear response history analysis is not practical, and the simplified analysis procedure as described in FEMA P-58, Volume 1 should be used for preliminary performance assessments.

This section describes several shortcuts that can be used in conducting preliminary analyses to reduce the effort to a level commensurate with preliminary design. Engineers are cautioned that these shortcuts may introduce additional bias, either conservative or unconservative, and substantial additional uncertainty, into the performance assessment. Because these shortcuts are not recommended for use in verification of performance capability of final designs, it is not necessary to account for this additional bias and uncertainty. However, knowing that additional bias and uncertainty could potentially exist reinforces the need to conduct a final design verification using a complete FEMA P-58 performance assessment.

The FEMA P-58 methodology typically requires determination of the following demand parameters for each level of ground shaking for which performance is being assessed:

- Peak transient story drift in each of two orthogonal directions
- Residual story drift in each of two orthogonal directions
- Peak floor acceleration in each of two orthogonal directions

In addition to the above parameters, it is also necessary to estimate peak floor velocity if the performance model includes fragilities for unanchored equipment or contents.

The most direct way to obtain demand parameters for assessment of a preliminary design is to construct a simple elastic analytical model of the seismic force-resisting system, in each primary direction of the building, using the simplified analysis procedures of FEMA P-58, Volume 1.

4.3.2.1 Structural Period

The first mode period of vibration, T, of the structure in each primary direction of response is a key parameter used to estimate structural demands. For preliminary performance assessment, the approximate fundamental period can be calculated using ASCE/SEI 7-16 Section 12.8.2.1 Equation 12.8-7:

> **Short Cut for Preliminary Design**
> The approximate fundamental period can be calculated using ASCE/SEI 7-16 Equation 12.8-7.

$$T_a = C_t h_n^x \tag{4-1}$$

where h_n is the structural height as defined in ASCE/SEI 7-16, and C_t and x are determined per ASCE/SEI 7-16 Table 12.8-2.

Use of this approximate period formula affords several advantages. First, it allows rapid calculation of the structural period based on building height and the type of seismic force-resisting system. Second, approximate periods are calibrated to the measured response of real buildings, and inherently account for the stiffening (period shortening) effects of gravity framing and nonstructural systems. Periods obtained by analysis will not include these effects, unless the engineer has deliberately included representation of additional stiffening elements in the analytical model, which is not typically done. For flexible structural systems, such as steel moment-resisting frames, analytical period determination using models that include only the seismic force-resisting system can over-estimate periods by 40%, or more. This typically results in over-prediction of consequences (i.e., poorer performance). Use of the code-specified approximate period formula avoids this potential inaccuracy.

4.3.2.2 Yield Strength

The yield strength, V_y, under lateral forces, is a key parameter used to estimate demands in the simplified analysis procedure. FEMA P-58, Volume 1, Section 5.2.1 suggests that for preliminary design, an approximate approach to estimating building yield strength can be based on building design parameters. This approach is modified for preliminary design using a bias factor, B.

> **Short Cut for Preliminary Design**
> Building yield strength is determined based on design parameters and a bias factor.

Accordingly, the following modified approach for estimating yield strength, V_y, may be used in assessing the performance of preliminary designs:

$$V_y = \frac{2BS_{Da}\left(T_1\right)}{R / I} W \tag{4-2}$$

where:

V_y = yield strength

B = bias factor

$S_{Da}(T_1)$ = design spectral acceleration at the fundamental period of the building, as determined from ASCE/SEI 7-16

R = response modification coefficient for the structural system under consideration, as specified in ASCE/SEI 7-16

I = Importance Factor for the building used in design

W = effective seismic weight of building, as defined in ASCE/SEI 7-16

The bias factor, B, is used to adjust the estimated yield strength of the building to account for deliberate design decisions that strengthen the building beyond what is required in the building code. For example, if the engineer elects to design the structure twice as strong as the minimum code-specified base shear strength as a means of improving its performance capability, the value of B should be taken as 2. This is a convenient way to rapidly explore the effects of alternative building strength levels on performance. The bias factor, B, can also be used to account for the strength of an existing building, which may be less than what is currently specified in the building code. As an example, if a building was designed in accordance with an earlier edition of the code that utilized 75% of the strength specified in the current code, the value of B should be taken as 0.75.

In the case of existing buildings, an estimate of the yield strength may be available as a result of a completed ASCE/SEI 41 Tier 3 evaluation. Where available, results of prior detailed analyses should be used as appropriate.

4.3.2.3 Strength Ratio

The strength ratio, S, is used to determine demands in the FEMA P-58 simplified analysis procedure. In accordance with FEMA P-58, Volume 1 the strength ratio is taken as:

$$S = \frac{S_a(T_1)}{V_y}W \tag{4-3}$$

where $S_a(T_1)$ is the spectral acceleration at the fundamental period, T_1, for the intensity of shaking at which performance is being evaluated. All other terms are as previously defined.

4.3.2.4 Uncorrected Story Drift Ratio

The uncorrected story drift ratio, Δ_i, at each story "i" can be computed using an analytical model and the formula contained in FEMA P-58, Volume 1, Section 5.3.2. Alternatively, the story drift at each level can be taken as:

$$\Delta_i = \frac{DS_a(T_1)\Delta_a}{C_d S_{Da}(T_1)} \tag{4-4}$$

where:

D = fraction of the allowable story drift ratio for the structural system, per ASCE/SEI 7-16 Section 12.12, that the engineer elects to target in the design

Δ_a = allowable story drift ratio, per ASCE/SEI 7-16 Section 12.12

C_d = deflection modification coefficient for the specified structural system, per ASCE/SEI 7-16 Section 12.2

and other terms are as previously defined. Note that for existing buildings it will be necessary to perform analysis to determine the values of Δ_i or select a target value that the retrofit is intended to achieve.

Short Cut for Preliminary Design
A simplified approach to calculating uncorrected story drift ratio is provided.

4.3.2.5 Median Story Drift Ratio

If the strength ratio, S, at the ground motion intensity level of interest has a value of 1 or less, the median story drift ratio, Δ_i^*, can be taken as the uncorrected value, Δ_i, computed in accordance with Equation 4-4. If the strength ratio, S, has a value exceeding 1, the values of $S_a(T)$, S, T, and Δ_i computed in accordance with the procedures above should be used in "Step 3" of FEMA P-58, Volume 1, Section 5.3.2 to correct story drift ratios to account for inelastic behavior and higher mode effects.

4.3.2.6 Median Floor Acceleration

The median floor acceleration, a_i^*, at each story "i" is calculated following the procedures of "Step 4" of FEMA P-58, Volume 1, Section 5.3.3 to estimate peak floor acceleration from peak ground acceleration. The strength ratio, S, is taken as previously computed in Section 4.3.2.3.

The value of peak ground acceleration (PGA) at the site can be calculated for the ground motion of interest from the equation:

$$\text{PGA} = \frac{S_{DS}}{2.5}\frac{S_a(T)}{S_{Da}(T)} \tag{4-5}$$

where S_{DS} is the value of the short period design spectral acceleration for the building and $S_a(T)$ and $S_{Da}(T)$ are as defined previously. Alternatively, PGA may be obtained directly from a site-specific seismic hazard report, if available.

4.3.2.7 Median Peak Ground Velocity

If the building performance model includes fragilities that depend on peak floor velocity, the median peak floor velocity, v_i^*, is computed at each story "i" following the procedures of "Step 5" of FEMA P-58, Volume 1, Section 5.3.2 to estimate peak floor velocity from peak ground velocity.

4.3.2.8 Dispersions

Demand dispersions are computed in accordance with the recommendations of FEMA P-58, Volume 1, Section 5.3.2.

4.3.3 Demand Estimation for Structures with Supplemental Protective Systems

This section describes modification to the approximate procedures in Section 4.3.2 for structures that incorporate supplemental protective technologies.

4.3.3.1 Seismic Isolation

As a general rule of thumb, the response of an isolated structure can be reduced to approximately 20% of the response of fixed base structures through the combined effects of period lengthening and supplemental damping. To explore the potential benefits of seismic isolation in preliminary design, demand calculations in Section 4.3.2 can be modified using the following approximations:

- The period of the structure can be taken as that produced by the isolation system, which is typically in the range of $2 \leq T \leq 3$ seconds.
- Effective viscous damping of 30% can be assumed. This has the effect of reducing spectral amplitudes by about 50%.
- Effective response can be reduced by $1/T$ plus the added effect of damping.
- To approximately evaluate the effect of the system, 1/4 of the intensity of motion can be used to check performance.

Short Cut for Preliminary Design
Demand estimates for an isolated structure are half of those for a fixed base structure.

These approximations can be implemented by halving the values of $S_a(T)$, PGA, and PGV computed for a fixed-base structure on the site. Demand dispersions should be computed as for a fixed-base structure.

4.3.3.2 Damping Systems

Short Cut for Preliminary Design
Demand estimates for a damped structure are half of those for a fixed base structure.

As a general rule of thumb, properly designed passive energy dissipation systems can reduce the effective response by 50% compared to an undamped structure. To explore potential benefits of a damping system in preliminary design, demand calculations in Section 4.3.2 can be modified using the following approximations:

- Effective viscous damping on the order of 30% to 40% can be assumed.
- To approximately evaluate the effect of the system, 1/2 of the intensity of motion can be used to check performance.

These approximations can be implemented by halving the values of $S_a(T)$, PGA, and PGV computed for an undamped structure. Demand dispersions should be computed as for an undamped structure.

4.4 Direct Design Procedure for Preliminary Design

The direct design procedure is based on the use of an interactive spreadsheet tool, the *Performance Estimation Tool* (PET), which allows direct determination of required stiffness and strength of a structural system that will achieve specific performance objectives, for the systems and occupancies addressed within the available performance data. Once the necessary design strength and story drift are known, the engineer can proceed to select structural member sizes that will provide the required level of strength and stiffness. The direct design procedure is applicable if the building under consideration is:

> **Short Cut for Preliminary Design**
> *Performance Estimation Tool* (PET) allows direct determination of the required strength and stiffness of a structural system to achieve specified performance objectives.

- One of the following structural systems: Special reinforced concrete shear wall (Special RCSW), reinforced concrete special moment-resisting frame (RC SMRF), steel special moment-resisting frame (Steel SMRF), special steel concentrically-braced frame (Steel SCBF), or steel buckling-restrained braced frame (Steel BRBF)
- Office or healthcare occupancy
- Risk Category II or IV

Reasonable approximations can be made to extrapolate results beyond the data available within the tool. For example, the performance of masonry shear wall structures could be considered similar to the performance of concrete shear wall structures for preliminary design purposes. Extrapolation is discussed in Section 4.4.2.

If the building under consideration is not one of these systems or occupancies, and cannot reasonably be extrapolated from similar results available within the tool, then the structural system should be selected and designed using the general procedure described in Section 4.3.

4.4.1 Performance Estimation Tool

The *Performance Estimation Tool* (PET) is provided in electronic format in FEMA P-58, Volume 3. The tool was developed based on an application of the FEMA P-58 methodology to a wide range of archetypical buildings conforming to the seismic design requirements of ASCE/SEI 7-10. The tool returns the performance of simple buildings (with no irregularities in stiffness, mass, and configuration) based on selected combination of seismic force-resisting system, occupancy type, Risk Category, building height, and seismic hazard from the available options contained within the database of performance assessment results. Results are presented in terms of FEMA P-58 performance metrics, including repair cost, repair time, casualties, unsafe placard, probability of collapse, probability of reparability, and probability of unrepairable permanent drifts for a range of ground motion intensities. The tool does not address environmental impacts. If environmental impacts are critical to achieving the targeted performance objectives, preliminary design should be conducted using the general procedure described in Section 4.3.

The *Performance Estimation Tool* explicitly covers the following five structural systems, considering low-, mid- and high-rise buildings in office occupancies, and low- and mid-rise buildings in healthcare occupancies:

- Special RCSW
- RC SMRF
- Steel SMRF
- Steel SCBF
- Steel BRBF

The tool addresses the following three seismic hazard levels:

- SDC E and F (S_{DS} = 1.33g, S_{D1} = 0.75g)
- SDC D (S_{DS} = 1.00g, S_{D1} = 0.60g)
- Low SDC D (S_{DS} = 0.50g, S_{D1} = 0.35g)

and provides performance estimates at five levels of shaking intensity, as a fraction of Maximum Considered Earthquake (MCE) intensity:

- 20% MCE
- 40% MCE
- 67% MCE
- 80% MCE
- 100% MCE

Appendix A provides instructions on how to use the *Performance Estimation Tool* (PET) to select from the range of available options, adjust design strength and stiffness, and review the resulting performance assessment results.

4.4.2 Extrapolation

The *Performance Estimation Tool* directly addresses only the seismic force-resisting systems and occupancies noted above. Although these represent only a fraction of all permissible seismic force-resisting systems included in ASCE/SEI 7, they cover a wide range of system strengths, stiffnesses, and ductilities, and allow for reasonable extrapolations to be made for systems with similar characteristics.

4.4.2.1 Extrapolation to Other Systems

For preliminary design, it is reasonable to extrapolate results obtained for Special RCSW systems to Special Masonry Shear Wall systems and Ordinary Reinforced Concrete Shear Wall systems, where the building code permits the use of such systems. Similar extrapolation of results for Steel SCBF systems to Ordinary Concentrically Braced Frame systems, and for Steel SMRF and RC SMRF systems to Intermediate Moment-Resisting Frame systems are also possible.

4.4.2.2 Extrapolation to Other Occupancies and Uses

The *Performance Estimation Tool* addresses two occupancies classified as Risk Category II, and two occupancies classified as Risk Category IV. Risk Category II occupancies include commercial office and medical office buildings, and Risk Category IV occupancies include emergency operations centers and acute-care hospital buildings. In each Risk Category, one occupancy represents relatively low building value (i.e., office occupancies), and one represents relatively high building value (i.e., healthcare occupancies).

For preliminary design, the expected performance of other occupancies can be approximated using a building fitting the same combination of Risk Category and building value. For example, a laboratory building having a high building value, but not containing significant hazardous materials, could be classified as Risk Category II, and the measured performance of the medical office building could be used as a starting point for preliminary design of the laboratory building.

4.4.2.3 Extrapolation to Supplemental Protective Systems

As discussed in Section 4.3.3, use of supplemental protective systems, such as base isolation or energy dissipation (damping) can reduce the demands on the structure by one-half. When base isolation and energy dissipation are used together, total demands can be reduced to as little as one-third of demands for a fixed-base structure.

Similarly, results in the *Performance Estimation Tool* can be extrapolated to supplemental protective systems by considering demand intensities that are adjusted based on the amount of demand reduction expected to be provided by the supplemental protective system that is used.

4.5 Other Factors Affecting Performance

4.5.1 Nonstructural Systems

The engineer generally has limited involvement in the specification of nonstructural components and systems during preliminary design. Unfortunately, in many projects, the engineer can have limited or no involvement in the specification of nonstructural components at any stage of design. Damage to nonstructural components and systems, however, can dominate measured performance, particularly in moderate levels of shaking. The following observations related to specification of nonstructural systems were developed based on FEMA P-58, Volume 5 studies:

- Exterior cladding and glazing systems are a major contributor to losses, especially in frame systems.
- Flooding due to piping failures is a significant contributor to repair costs and repair time.
- Ceiling damage is a significant contributor to repair costs, and, to a smaller degree, casualties.
- In healthcare occupancies, unanchored medical equipment is a major contributor to losses.
- Partitions are a significant contributor to losses.

Explicit coordination between the structural design and specification of nonstructural components is necessary to achieve targeted performance objectives. For example, in the design and installation of exterior enclosures, a specialty engineer is generally responsible to design the cladding system based on story drift ratios provided by the building engineer. Often, when the building engineer develops a structural design with reduced levels of story drift, this is used to allow the design of cladding, stairways, and other drift-sensitive components to reduced drift levels, which leaves these components vulnerable to damage. Alternatively, consideration should be given to selecting enhanced criteria that require minimal earthquake damage to cladding and other components, leading to the specification of design drift capacities for nonstructural components that substantially exceed story drifts that are expected to occur in the structural system.

Use of PACT provides the engineer with deaggregation plots identifying component contributions to loss, which assist the engineer in targeting major contributors to loss, and adjusting the design to minimize contributions to loss. Figures 4-1 and 4-2 show repair cost deaggregation plots associated with two reinforced concrete systems: Special RCSW and RC SMRF.

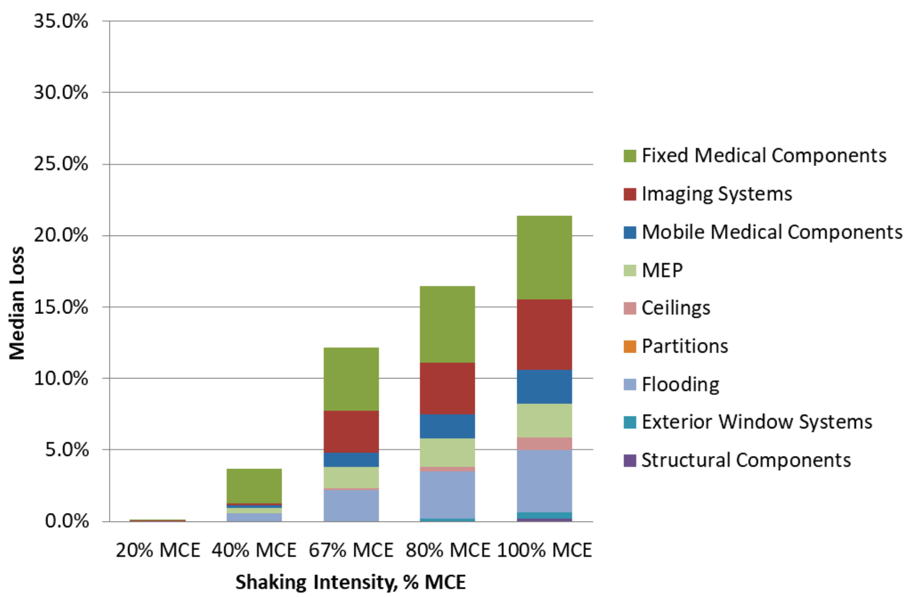


Figure 4-1 Plot showing structural and nonstructural component contributions to median repair costs, for mid-rise, Risk Category II, SDC D, Special RCSW system, healthcare occupancy.

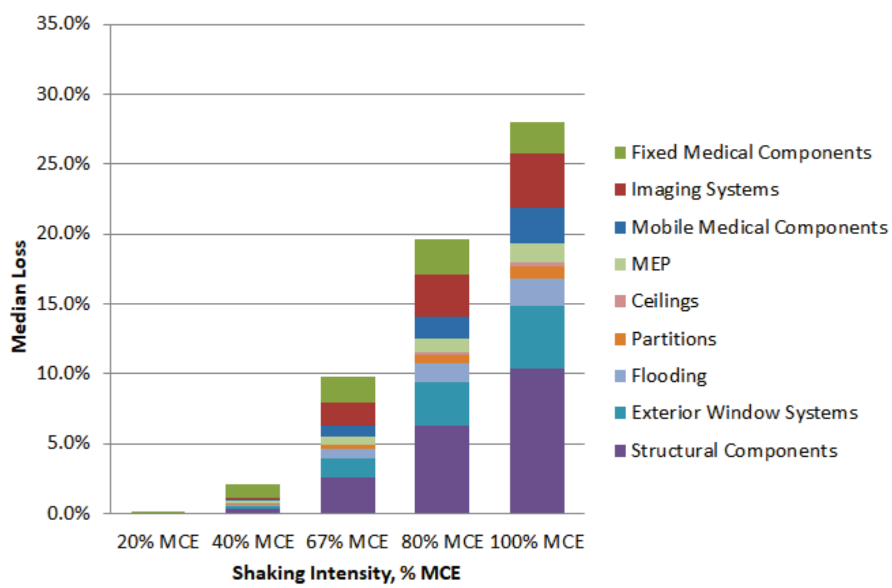


Figure 4-2 Plot showing structural and nonstructural component contributions to median repair costs, for mid-rise, Risk Category II, SDC D, RC SMRF system, healthcare occupancy.

A comparison between the plots at higher intensities shows that:

- In the stiffer shear wall system, losses associated with damage to acceleration-sensitive components, including MEP equipment, medical equipment, ceilings, and flooding, are proportionally larger.
- In the more flexible moment-resisting frame system, losses associated with damage to drift-sensitive components, including the structural frame and exterior window systems, are proportionally larger.

Deaggregation information is also useful for establishing seismic design criteria for components that are critical due to high cost of initial investment, or long lead time for replacement.

4.5.2 Building Configuration

Observations of building performance in past earthquakes have consistently shown that building configuration has a significant impact on seismic performance. Buildings without significant irregularities in stiffness, mass, and configuration have exhibited better performance than buildings with irregularities. The building code includes provisions that are intended to address irregularities, including requirements related to modeling, selection of analysis procedures, and required redundancy. The building code prohibits certain irregularities that are judged to be unacceptable in areas of higher seismicity.

Experience strongly suggests that eliminating, or at least minimizing, irregularities is a more effective solution for buildings with higher performance targets. To the extent the building under consideration is irregular, performance predicted using the direct design procedure in Section 4.4 would overestimate the actual performance capability. Evaluation of irregularity effects would require a full FEMA P-58 assessment based on detailed structural analysis of the building considering the presence of irregularities, using the general design procedure in Section 4.3.

4.6 Final Design and Performance Verification

The last step of the performance-based design process involves assessment of the performance capability of the final design, using detailed and specific information, to ensure that the resulting design meets the targeted performance objectives.

Final performance verification should be conducted using the performance assessment procedures in FEMA P-58, Volume 1. Typically, it will be necessary to advance the design to at least a Design Development level of completion before sufficient information is available to allow a meaningful detailed performance evaluation to be conducted. Final performance verification should use a building-specific performance model and an appropriately detailed structural analysis of the building, as depicted in the construction documents.

Building performance can be dominated by the performance of nonstructural components and systems. Thus, it is imperative that the engineer work with the other design disciplines to ensure that the fragilities used in the building performance model are appropriate to the actual nonstructural components specified for installation.

It is also essential to confirm that structural and nonstructural components are constructed as assumed in the design, and with appropriate levels of quality assurance. The engineer should consider extending structural observation activities, normally performed on structural components, to the installation of nonstructural components and systems that are critical to meeting the targeted performance objectives.

Appendix A
Performance Estimation Tool User Manual

The *Performance Estimation Tool* (PET) is an interactive spreadsheet provided in FEMA P-58, Volume 3, *Supporting Electronic Materials and Background Documentation*. The tool was developed from an application of the FEMA P-58 methodology to 1,755 archetypical buildings conforming to the seismic design requirements of ASCE/SEI 7-10, *Minimum Design Loads for Buildings and Other Structures*, (ASCE, 2010) for different structure types and different occupancies. The tool was originally developed to view and analyze data from these assessments, and overall results and conclusions from these data are summarized in FEMA P-58, Volume 5.

The *Performance Estimation Tool* can also be used as a design aid to quickly determine the level of strength and story drift necessary to achieve specific performance objectives for the systems and occupancies represented within the database. Once the required shear strength and design story drift are known, designers can proceed in selecting member sizes that result in a structural system with the necessary strength and stiffness.

A.1 Design Space

The *Performance Estimation Tool* incorporates the concept of a code-conforming design space that bounds the possible archetype designs and represents a reasonable range of lateral strengths and stiffnesses that would be expected in typical modern buildings designed in accordance with ASCE/SEI 7-10 seismic design requirements. The design space is intended to capture the range of structural design choices, from buildings designed to code-specified minimum base shear and maximum allowable story drift to those designed more conservatively in whole or in part.

Figure A-1 shows a typical design space with 13 points used to characterize archetypes with different strength and stiffness combinations. Lateral stiffness, in terms of story drift ratio, is presented on the horizontal axis, and lateral strength, as a multiple of the minimum design base shear strength, is presented on the vertical axis. The four corners of the design space represent the limits of the combinations of lateral strength and stiffness considered in the study. Point 1 represents a structure with a low design story drift ratio and minimum permitted lateral strength. Point 2 represents theoretical code-minimum design, which is a structure having the maximum practical design story drift ratio and code-minimum lateral strength. Point 3 represents the stiffest, strongest structure considered in the study. Point 4 represents a flexible structure having the maximum practical design story drift ratio and a high level of lateral strength.

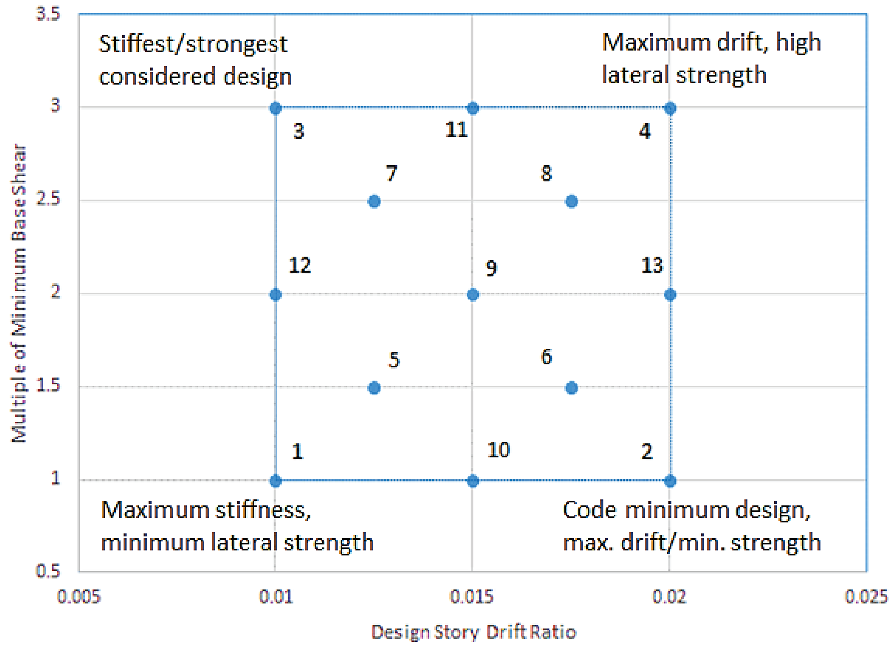


Figure A-1 Typical design space showing 13 points used to characterize the different strength and stiffness combinations of each archetype.

Seismic requirements only specify the minimum strength and maximum allowable drift boundaries of the design space. The design space boundaries vary for each seismic force-resisting system based on the strength and stiffness characteristics of typical buildings utilizing these systems. Design space boundaries and parameters for representative designs are presented in FEMA P-58, Volume 5.

A.2 Usage Notes

The *Performance Estimation Tool* was created in Microsoft Office 2013 as a macro enabled Excel file (.xlsm). The tool uses Excel macros, and macros must be enabled for the tool to run. It contains several worksheets, accessed as tabs, and labeled as follows:

- **Instructions.** The Instructions tab summarizes important information about the use of the tool.
- **User Interface.** The User Interface tab is used for selecting input parameters and obtaining the results.

- **Detailed Plots.** The Detailed Plots tab presents additional, more detailed information in graphical format for each loss metric shown on the User Interface tab.

In each tab, users access all options through of grey-shaded buttons, drop-down menus, and sliders located on the bottom and right side of the design space. Information should not be typed into any of the cells, especially the selection cells identified with heavy black borders.

A.3 User Interface Tab

Figure A-2 shows the PET User Interface tab. The left side of the tab is the user input interface. The user may select any combination of seismic force-resisting system, occupancy type, Risk Category, building height, and seismic hazard from the available options. Risk Category II office occupancies will allow selection of low-, mid-, and high-rise buildings, but healthcare occupancies and Risk Category IV office occupancies are limited to low- and mid-rise selections. The available gradient in seismic hazard level (i.e., Low SDC D, SDC D and SDC E/F) is representative of the Seismic Design Category D-E transition. The figure shows the tool with the following selections: special steel moment-resisting frame ("Steel SMRF"), "office" occupancy, Risk Category "II", "mid-rise" building height, and "SDC D" hazard level.

Figure A-3 shows the stiffness and strength input interface, including the design space graphic, which shows the boundaries of the design space for the selected seismic force-resisting system. Each point within the design space is characterized by a design story drift ratio and design strength expressed as a multiple of minimum base shear. The green dot indicates the location of the representative design within the design space. The red dot reflects the current selection of stiffness and strength within the design space. The red dot can be moved using the sliders located along the bottom and right side of the design space, or through selections from dropdown menus associated with the buttons for multiple of minimum base shear and design story drift. In the figure, input fields indicate the selection of a design story drift ratio of 0.015 and base shear ratio of 2.5.

Once data have been entered, the User Interface tab provides graphs showing estimates of building performance in terms of median, mean, and 90th percentile repair costs and repair times; probability of collapse; probability of reparability; and probability of unrepairable permanent drifts for different intensities of ground motion expressed as a percentage of the MCE shaking intensity at the building site. A change in any of the input parameters automatically updates all of the graphs.

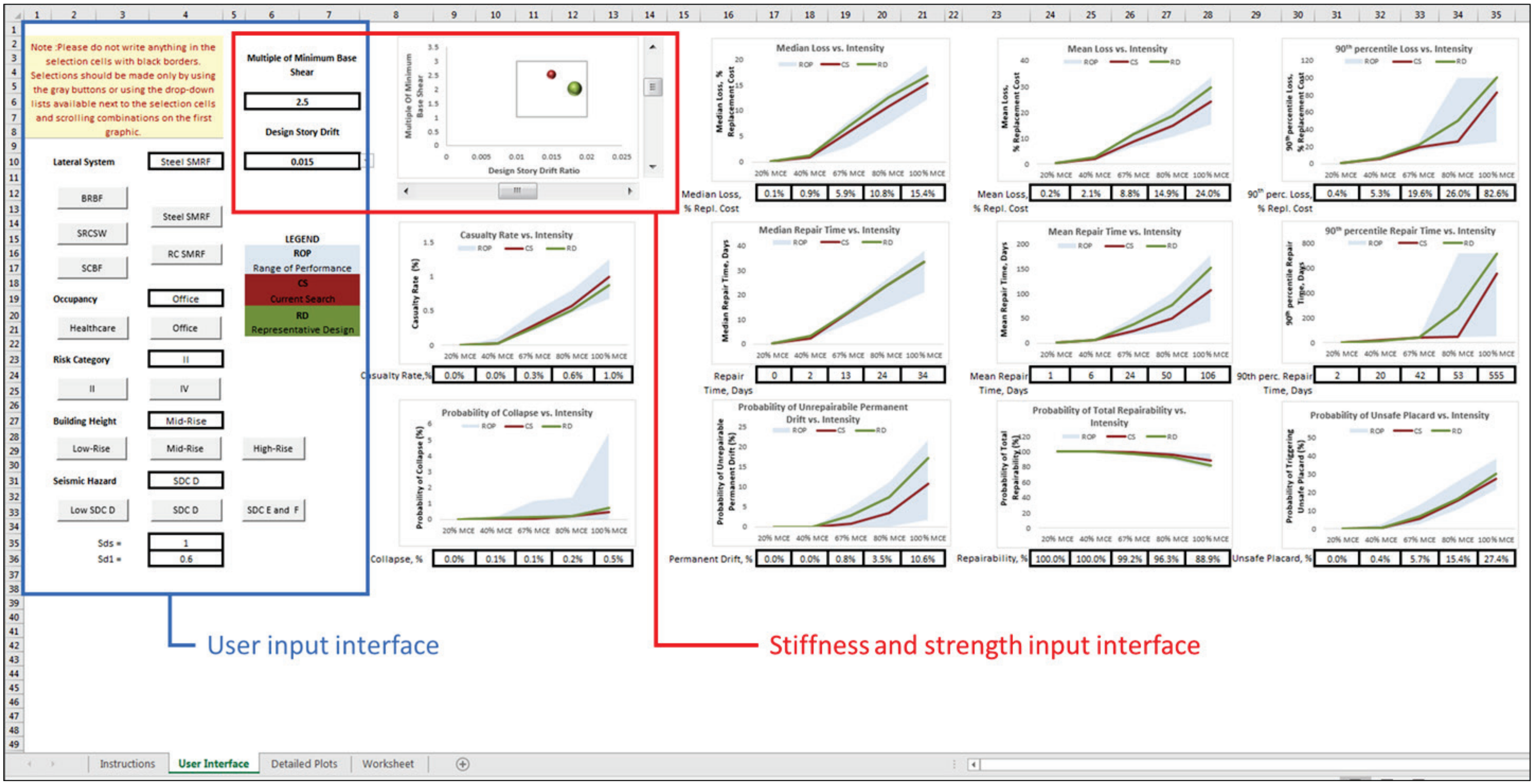


Figure A-2 PET User Interface tab.

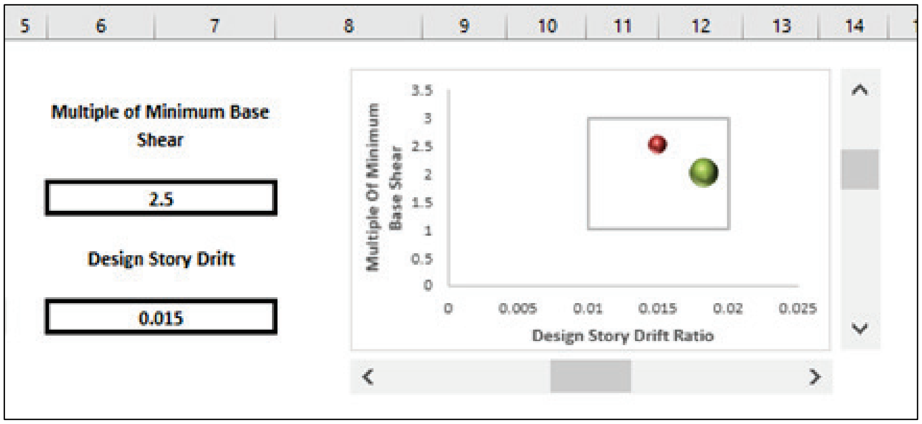
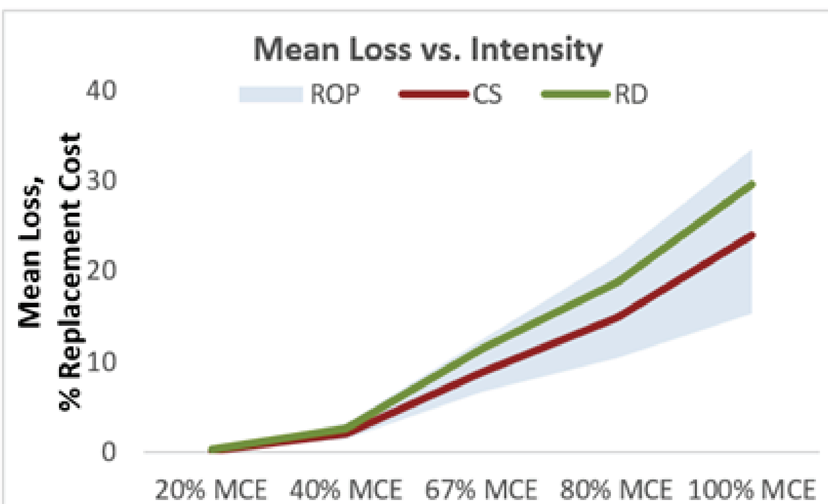


Figure A-3 Stiffness and strength input interface and design space graphic on the User Interface tab.

Figure A-4 provides an example of one graph showing mean repair cost expressed as percentage of replacement cost. In all graphs, a blue shaded area indicates the range of performance (ROP) for all buildings within the design space. A green line indicates the performance of the representative design (RD) for the selected system, and a red line indicates the performance of the current search (CS) parameters including the selected values of story drift ratio and base shear multiple. Performance values for current search (CS) parameters are also tabulated below the graph at each intensity level.



Mean Loss, % Repl. Cost	0.2%	2.1%	8.8%	14.9%	24.0%

Figure A-4 Graph showing mean repair cost as a percentage of replacement cost on the User Interface tab.

A.4 Detailed Plots Tab

The Detailed Plots tab provides all data for the parameters currently selected in the User Interface tab in larger scale and with additional detail. The tab displays one detailed plot at a time for the selected performance metric. Results for different performance metrics can be accessed through gray-shaded buttons on the left side of the tab. Figure A-5 provides a detailed plot of mean repair cost versus intensity, which is a more detailed version of the information shown in Figure A-4. Similar to Figure A-4, the red line shows the performance of the current search parameters, and the green line shows the performance of a representative building design for the selected system. The two blue lines indicate an upper and lower bound characterizing the range of performance considering all buildings within the design space. The performance of the current search, representative design, and bounds for the performance range are also tabulated below the plot.

	20% MCE	40% MCE	67% MCE	80% MCE	100% MCE
Upper Bound	0.2	3.2	12.4	21.6	33.5
Lower Bound	0.1	1.4	6.7	10.4	15.3
Current Search	0.2	2.1	8.8	14.9	24.0
Representative Design	0.2	2.6	11.4	18.8	29.7

Figure A-5 Detailed plot of mean repair cost versus intensity.

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