Seismic Performance Assessment of Buildings

Volume 5 – Expected Seismic Performance of Code-Conforming Buildings

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Cover photograph – Buildings comprising the San Francisco skyline, circa 2018 (courtesy of Magnusson Klemencic Associates/ Steve Proehl).

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, *Seismic Performance Assessment of Buildings, Volume 5 – Expected Seismic Performance of Code-Conforming 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 work to quantify the performance capability of typical buildings designed to current building code requirements, the resulting performance of code-conforming buildings in terms of FEMA P-58 probabilistic performance metrics, and a framework for future recommended performance objectives based on findings from this work.

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

Stephen A. Mahin

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.

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.

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Chapter 1
Introduction

This report is the fifth in a series of volumes comprising the FEMA P-58, *Seismic Performance Assessment of Buildings, Methodology and Implementation* (FEMA, 2012; 2018). This volume describes the work performed to quantify the seismic performance capability of typical buildings designed to current building code requirements, the resulting performance of code-conforming buildings in terms of FEMA P-58 probabilistic performance metrics, and a framework for future recommended performance objectives based on findings from this work.

1.1 Background

In 2012, the Applied Technology Council (ATC), under contract with the Federal Emergency Management Agency (FEMA), completed the development of next-generation seismic performance assessment procedures. Collectively referred to as FEMA P-58, *Seismic Performance Assessment of Buildings, Methodology and Implementation*, the fundamental products in this series included:

- 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)

FEMA P-58 provides a general methodology and recommended procedures to assess the probable seismic performance of individual buildings based on their unique site, structural, nonstructural, and occupancy characteristics. 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 embodied energy and carbon. The methodology and procedures are applicable to new or existing buildings, and can be used to: (1) assess the probable performance of a given building; (2) design new buildings to be capable of providing desired performance; or (3) design seismic upgrades for existing buildings to improve their performance.

This work was the result of a series of FEMA-funded efforts to develop next-generation performance-based seismic design guidelines for new and existing buildings, which were initiated in 2001, and would become known as the ATC-58 series of projects. The overall program of development was based on the FEMA 349, *Action Plan for Performance-Based Seismic Design* (FEMA, 2000), developed by the Earthquake Engineering Research Institute (EERI), and subsequently modified and published as FEMA 445, *Next-Generation Performance-Based Seismic Design Guidelines, Program Plan for New and Existing Buildings* (FEMA, 2006). This program outlined 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.

Work on Phase 1 was completed in 2012 with the publication of the initial FEMA P-58 series of volumes. Work on Phase 2 was initiated in the same year.

1.2 Purpose

The purpose of the Phase 2 work was to utilize the FEMA P-58 assessment methodology developed under Phase 1 to establish recommendations for specifying seismic performance objectives in terms of FEMA P-58 performance metrics, and to develop guidelines for effectively designing buildings to achieve the desired performance using FEMA P-58 procedures. This included guidance and recommendations to:

- assist decision-makers in selecting appropriate performance objectives for buildings of different occupancies;
- assist structural engineers in identifying appropriate structural and nonstructural design strategies to achieve specific performance objectives; and
- assist structural engineers in efficiently developing preliminary designs with minimal iteration during the design process.

As part of Phase 2, the FEMA P-58 methodology was exercised in assessing the performance of code-conforming buildings. Technical improvements and updates to the methodology were also developed, as necessary, to take advantage of the latest research and to bring assessment results into better alignment with expectations based on performance 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.

Work conducted under Phase 2 has updated and expanded the FEMA P-58, *Seismic Performance of Buildings, Methodology and Implementation* series of volumes 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)

This report (Volume 5) describes the application of the FEMA P-58 assessment methodology to a group of archetypical buildings representative of structures conforming to the seismic design requirements of the current building code. The purpose of this work 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 simplified performance-based design guidance.

1.3 Evolution of Seismic Performance Expectations for Code-Conforming Buildings

It is commonly understood that building codes provide minimum requirements for protection of public safety and welfare. The stated performance expectations of seismic design requirements in building codes, however, have been continually evolving with changes in modern building codes and standards, particularly over the past decade.

Early seismic design requirements began as prescriptive rules for avoiding catastrophic failures and life-threatening damage that was observed in past earthquakes. Rules were created to reduce or eliminate known or perceived vulnerabilities, which were tested, and updated, if necessary, based on observations of building performance in subsequent earthquakes. More recent design requirements include prescriptive criteria for selecting, proportioning, and detailing structural and nonstructural components. Although many of these criteria were developed with the intent of providing some level of seismic performance, the intended performance has been described, for the most part, in general, qualitative terms. The actual ability of code-compliant designs to provide the intended level of performance is not known.

The Structural Engineers Association of California (SEAOC) *Recommended Lateral Force Requirements* (SEAOC, 1973) is often cited as an early statement of the performance expectations associated with seismic design provisions. The SEAOC "Blue Book," as it was called, confirmed public safety as the primary intent of the building code, and further stated that seismic design requirements were expected to result in structures that: (1) resist minor earthquakes without damage; (2) resist moderate earthquakes without structural damage but some damage to nonstructural components; (3) resist major earthquakes with substantial structural and nonstructural damage; and (4) resist the most severe earthquakes without structural collapse (FEMA, 2015b).

Beyond safety objectives, the SEAOC Blue Book acknowledged that some seismic design requirements were also intended to minimize property damage and preserve functionality in cases such as essential, or otherwise important structures. In the National Earthquake Hazards Reduction Program (NEHRP) *Recommended Provisions for the Development of Seismic Regulations for New Buildings* (FEMA, 1988), the stated performance intent of the *Provisions* was to "minimize hazard to life for all buildings," "increase the expected performance of higher occupancy structures," and "improve the capability of essential facilities to function during and after an earthquake." This remained the basic underlying philosophy of the *Provisions* until the 2009 Edition (FEMA, 2009a), when the performance statement was revised to also include consideration of minimizing structural and nonstructural repair costs "where practical to do so."

To improve expected performance and increase the chances that higher occupancy and essential facilities will remain functional, seismic design requirements have long included higher structural design forces, lower permissible structural drifts, and additional bracing, anchorage, and testing requirements for nonstructural components. Such measures are expected to reduce potential damage, minimize associated repair costs, and preserve function, but the actual ability to achieve stated performance expectations has not been quantitatively validated (Mieler and Mitrani-Reiser, 2018).

A quantitative definition of the collapse safety objective was provided in FEMA P-695, *Quantification of Building Seismic Performance Factors* (FEMA, 2009b), taken as a 10% conditional probability of collapse given Maximum Considered Earthquake (MCE) shaking. This probabilistic definition of collapse safety was used by the United States Geological Survey (USGS) to develop the risk-targeted Maximum Considered Earthquake (MCE_R) adopted as the basis of seismic hazard in ASCE/SEI 7-10, *Minimum Design Loads for Buildings and Other Structures* (ASCE, 2010).

In the commentary to ASCE/SEI 7-10, structural reliability concepts were introduced to quantitatively define the performance expectations of the standard. Acceptable reliabilities (in terms of annual probabilities of failure) were quantified for typical load conditions, and extended to earthquake loading using the FEMA P-695 probabilistic definition of collapse safety. For earthquake load conditions, anticipated reliability was anchored to the collapse performance of normal occupancy structures based on the 10% conditional probability of collapse given MCE_R shaking intensity, and anticipated reliabilities for higher occupancy or essential structures were adjusted considering increased reliabilities presumed to occur when structures were designed using an importance factor.

In ASCE/SEI 7-16, *Minimum Design Loads and Associated Criteria for Buildings and Other Structures* (ASCE, 2017a), structural reliability concepts introduced in the commentary to ASCE/SEI 7-10 were incorporated into the provisions of the standard to define performance expectations. Performance-based procedures were revised to require explicit consideration of structural reliability, and performance-based design of structures subjected to earthquakes must meet reliability targets that are now specified in the standard. As was the case in ASCE/SEI 7-10, reliability targets for earthquake load conditions were anchored to a 10% conditional probability of collapse given MCE_R shaking intensity for normal occupancy structures. Current reliability targets in terms of conditional probabilities of collapse for higher occupancy structures and essential facilities are 5% and 2.5%, respectively, when subjected to MCE_R shaking intensity. Structures designed to the prescriptive requirements of the standard (i.e., not using the performance-based procedure) are deemed to comply with these reliability targets without explicit confirmation.

ASCE/SEI 7-16 provisions also require that structural and nonstructural components meet defined serviceability and functionality requirements, although specific reliability targets are not provided. The commentary to ASCE/SEI 7-16 provides the following performance expectations for typical nonstructural components: (1) minimal damage, not likely to affect functionality in minor earthquake ground motions; (2) some damage that may affect functionality in moderate earthquake ground motions; and (3) major damage, but significant falling hazards are avoided, with likely loss of functionality in design earthquake ground motions. Use of a component importance factor is intended to provide higher levels of confidence that critical components will remain in place, sustain limited damage, and function after an earthquake, but this is recognized as having an indirect influence on the survivability of a component. The commentary to ASCE/SEI 7-16 also notes that serviceability needs are often subjective, preservation of function is broadly defined, and that structural fragilities for ensuring function are not well-established. For these reasons, the commentary acknowledges that the criteria for performance-based design for functionality are not absolute.

In the NEHRP *Recommended Seismic Provisions for New Buildings and Other Structures, Volume II: Part 3 Resource Papers* (FEMA, 2015b), a framework is proposed for extending the risk-targeted safety objective to develop quantitative functional and economic targets for design of structural and nonstructural components. The FEMA P-58 methodology is cited as a possible basis for estimating the resulting structural and nonstructural performance targets. Although a framework for future performance-based design criteria is proposed, the details are not complete, and the resource paper identifies many needs before implementation can be considered. These include: (1) probabilistic assessment of the performance that is provided by current seismic design requirements; (2) agreement on the definition of a functional level earthquake (FLE); (3) assessment of the level of functionality that is provided by current seismic design requirements; and (4) correlation and calibration of performance targets with stakeholder expectations and actual performance that is (or can be) achieved in earthquakes.

In summary, seismic design requirements have been trending towards more explicit statements of expected performance and development of more specific performance-based design criteria. Although the stated intent of seismic design requirements has included concepts of performance, functionality, and repair costs for some time, the actual ability of these requirements to achieve the stated performance intent, or to differentiate performance between normal occupancy and essential facilities, has not been validated.

1.4 FEMA P-58 Assessment of Code-Conforming Buildings

To date, alignment between current building code requirements and stated performance expectations is not known, and code-based performance objectives have not expressed in terms of FEMA P-58 performance measures. As a result, understanding the expected structural and nonstructural performance of code-conforming buildings in terms of FEMA P-58 performance metrics was considered an essential benchmark for informing recommendations on performance objectives and the development of guidelines for performance-based seismic design.

Damage to nonstructural components often accounts for the majority of losses in an earthquake. Modern code-conforming buildings subjected to moderately strong earthquake shaking are not expected to collapse, but nonstructural components can sustain costly and potentially disruptive damage. Evaluation of nonstructural performance in the past has relied heavily on post-earthquake observations, which are almost always qualitative, and difficult to interpret because the seismic design and quality of installation of nonstructural components are often not known with any certainty. FEMA P-58 loss estimates are generated using fragility data that reflects code-conforming design and detailing of nonstructural components. As such, the methodology can be used to obtain insight on the expected performance of code-conforming nonstructural components, which has not yet been obtained from post-earthquake observations alone.

A key task under Phase 2 was the assessment of code-conforming buildings using the FEMA P-58 methodology. Code-conforming buildings were taken as buildings complying with the requirements of ASCE/SEI 7-10 including Supplement 1, *Minimum Design Loads for Buildings and Other Structures* (ASCE, 2013). This work utilized the FEMA P-58 methodology and related products to evaluate the expected seismic performance over a range of buildings and systems meeting the structural and nonstructural design requirements of ASCE/SEI 7-10.

1.5 Organization and Content

This volume presents the results of seismic performance assessments of code-conforming buildings using the FEMA P-58 methodology and expresses probable performance in terms of FEMA P-58 performance metrics.

Chapter 2 outlines the approach, discusses factors affecting seismic performance, and introduces the concept of the design space, which defines the likely combinations of lateral stiffness and strength for buildings of a given seismic force-resisting system, combination of occupancy and importance, and height.

Chapter 3 describes how the structural properties and structural demand quantities for each building archetype were derived.

Chapter 4 describes the structural and nonstructural fragility functions used in the performance assessments.

Chapter 5 presents performance assessment results for each system in terms of FEMA P-58 performance metrics, including repair costs, repair time, casualties, and unsafe placarding, and summarizes results by system type, occupancy, Risk Category, hazard level, and building height.

Chapter 6 provides an overall summary of results, generalizes system-specific results to quantify the overall expected performance of code-conforming buildings, and presents a framework for future recommended performance objectives defined in terms of FEMA P-58 performance metrics.

Appendix A describes the variation in structural properties with hazard level, and summarizes key structural properties for representative archetypical buildings designed at different hazard levels.

Appendix B summarizes types, quantities, and performance groupings of nonstructural components and medical equipment fragilities used in this study.

Appendix C describes the use of the *Performance Estimation Tool* (PET), which serves a repository of all assessment results and provides an interface for viewing the results for a given system and set of design assumptions.

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

Chapter 2
Assessment Approach

Performance of code-conforming buildings is not uniquely defined. Building codes establish minimum criteria that must be followed, but structural engineers have latitude in applying design requirements, and can make design decisions that significantly influence the performance of buildings in an earthquake.

Seismic force-resisting systems are selected from a variety of options. Although all buildings must meet certain minimum strength and stiffness requirements, structural engineers can choose to provide a structure that is stronger or stiffer than minimum requirements, or they can choose to design a structure that just meets code minimums. In some cases, practical constraints on combinations of lateral strength and stiffness for different systems can result in structures that exceed minimum requirements in one way or another.

In the case of nonstructural systems, structural engineers can exert explicit control over the design, and select enhanced seismic criteria to improve expected performance. Alternatively, structural engineers can follow typical practices of delegating the design and installation of nonstructural systems to vendors or sub-contractors as part of the construction process, which can vary in terms of its effectiveness for protecting nonstructural systems in an earthquake.

2.1 Overview

To quantify the performance capability of code-conforming buildings, 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. 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 (SRCSW).

Assessments were performed using the *Performance Assessment Calculation Tool* (PACT) version 3.03. Concurrent with this work, the FEMA P-58 methodology was undergoing technical update and improvement, and this version of PACT included updated fragilities and revised consequence functions reflecting the latest available information.

In the FEMA P-58 methodology, performance assessment requires basic information on the building configuration, structural and nonstructural systems, site characterization, earthquake hazards at the site, and building response given exposure to different intensities of earthquake shaking. To assess a wide range of code-conforming parameters, it was necessary to develop the required information for a large number of archetypical buildings, using simplified design and analysis procedures, and design values that were parametrically varied for different systems, heights, hazard levels, occupancies, and combinations of lateral strength and stiffness. The overall design and assessment approach included the following steps:

- Identification of design factors that affect seismic performance
- Determination of strength and stiffness combinations that bound a code-conforming design space
- Simplified design and determination of structural and nonstructural properties for a wide range of archetypes
- Estimation of building response
- Assembly of building performance models
- Assessment and summary of performance results

In this study, performance is measured in terms of repair cost, repair time, and probability of incurring an unsafe placard, as direct outputs of PACT. In addition, assessment data were exported and post-processed to derive additional metrics of interest, including casualty rates and repairability. These metrics are described in Chapter 5, along with the assessment results. Although the FEMA P-58 methodology is currently capable of assessing environmental impacts, this capability was not available at the time assessments were initiated, so environmental losses were not considered in the assessment of code-conforming buildings.

2.2 Factors Affecting Seismic Performance

Building design requires consideration of many factors that can significantly impact seismic performance. Factors known to affect seismic performance include:

- Selection of the seismic force-resisting system, including type, material, and level of ductile seismic detailing (i.e., special, intermediate, or ordinary)

- Design strength and lateral stiffness of the structure
- Structural configuration, including size, story height, bay spacing, distribution of structural elements, redundancy, and the presence of irregularities
- Robustness of structural member design and connection detailing
- Site characterization and site seismic hazard level
- Building occupancy, and its relation to Risk Category and Seismic Design Category
- Nonstructural design criteria and quality of installation
- Cost of construction, and construction budget

The structural engineer has significant control over some design considerations, and limited control over others. Table 2-1 categorizes the list of factors affecting seismic performance based on the estimated degree of control that a structural engineer might have over the design consideration.

Table 2-1 Factors Affecting Seismic Performance and Degree of Control in Seismic Design

Degree of Control	Design Consideration
High	Seismic force-resisting system selection; design strength and lateral stiffness; robustness of structural member design and connection detailing
Moderate	Structural configuration, including story height, bay spacing, distribution of structural elements, redundancy, and presence of irregularities; nonstructural design criteria and quality of installation of nonstructural components
Low	Building size, including floor plate and number of stories; occupancy; Risk Category; Seismic Design Category; cost of construction and construction budget
None	Site characterization and site seismic hazard (given a selected site)

Some aspects, such as Risk Category and Seismic Design Category are dictated by the building code, and other aspects, such as site characterization and seismic hazard level, are completely outside the control of the structural engineer. Each building project, however, is unique and in some cases the structural engineer may have more or less influence over a particular design consideration.

Table 2-2 shows design considerations that were parametrically varied in the archetype designs. Design considerations that were anticipated to have a high impact on performance were primary factors considered in this study, regardless of the degree of control that a structural engineer might have over the consideration. Other considerations, such as story height, bay spacing, floor plate area, redundancy, presence of irregularities, and site class were held constant to facilitate comparisons between archetypes with different seismic design criteria.

Table 2-2 Seismic Design Considerations Varied in Archetype Parameter Studies

Degree of Control	Design Consideration	Varied in Parameter Study
High	Seismic force-resisting system	■
	Design strength	■
	Design stiffness (drift ratio)	■
	Robustness of member design	
Moderate	Story height	
	Bay spacing	
	Redundancy	
	Presence of irregularities	
	Nonstructural design criteria	■
Low	Floor plate area	
	Number of stories	■
	Occupancy	■
	Risk Category	■
	Seismic Design Category	■
	Cost of construction; budget	
None	Site characterization (site class)	
	Site seismic hazard	■

2.3 Building Archetypes

To quantify the influence of seismic design considerations on performance, archetypical representations of buildings with a variety of code-conforming characteristics are needed. Archetype designs were developed for different seismic force-resisting systems, building configurations, occupancies, seismic hazard levels, and lateral strength and stiffness combinations.

2.3.1 Seismic Force-Resisting Systems

The seismic force-resisting systems considered in this study were selected to be representative of systems that would be used in commercial design applications, across a range of low-, mid-, and high-rise structures, in regions of high seismicity. Table 12.2-1 in ASCE/SEI 7-10 lists 85 seismic force-resisting systems. Of these, 68 systems can be used in regions of moderately high seismicity, and 48 systems can be used in regions of high seismicity. Height limits and other restrictions are placed on some systems, so preference was given to systems with a permissible height limit of at least 160 feet in Seismic Design Category (SDC) D to allow application across all building heights considered in the study. Bearing wall, dual, and composite systems were judged comparable in performance to building frame systems of a similar type, and were, therefore, not explicitly considered in this study.

As a result, the following five building frame and moment-resisting frame systems were selected as representative of a range of code-conforming systems:

- Steel special moment-resisting frames (Steel SMRF)
- Reinforced concrete special moment-resisting frames (RC SMRF)
- Steel buckling-restrained braced frames (Steel BRBF)
- Steel special concentrically-braced frames (Steel SCBF)
- Special reinforced concrete shear walls (Special RCSW)

2.3.2 Building Configurations

Building configuration includes building size and geometry considerations, such as floor plate area, bay spacing, story height, and number of stories. Building configuration also includes structural considerations, such as the distribution of seismic force-resisting elements, regularity (or the presence of irregularities), redundancy, torsion, diaphragm rigidity, and foundation flexibility.

In all cases, the structural configuration is a regular, redundant system, with well-distributed seismic force-resisting elements, and without the presence of plan or vertical irregularities. Diaphragms were assumed to be rigid, and torsion and foundation flexibility were ignored. The floor plans for each structural system are shown in Figures 2-1 through 2-3.

The geometric configuration of all archetypes is a rectangular floor plate with consistent bay spacing and identical overall dimensions of 100 feet wide by 140 feet long. Story heights are a constant 13 feet, but the number of stories varied from low-rise (2-story and 3-story), to mid-rise (5-story), and high-rise (12-story) archetypes. Office occupancies were configured to include all three height variants. Healthcare occupancies utilized only low- and mid-rise variants.

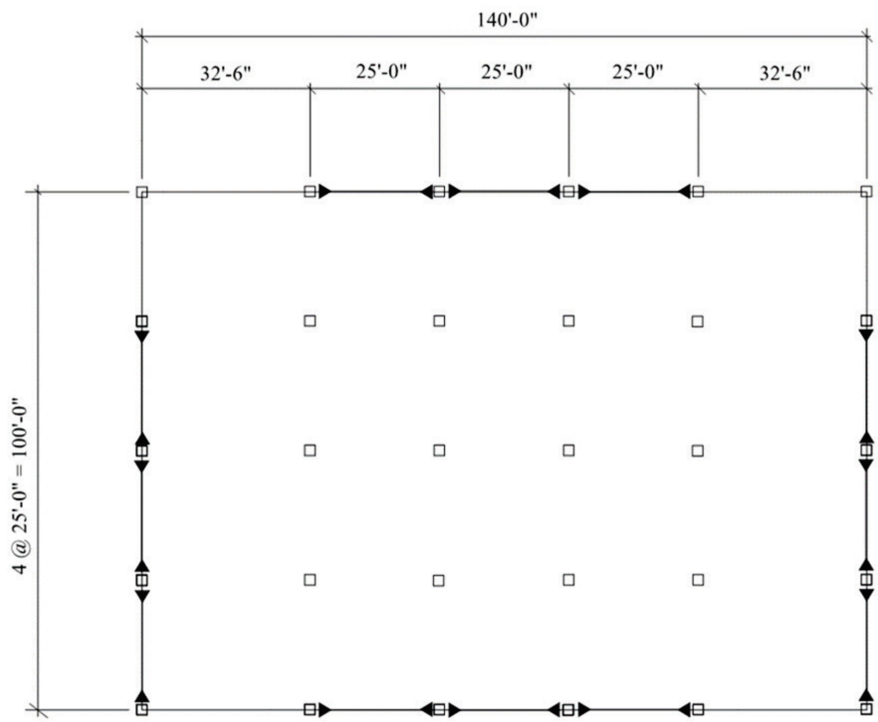


Figure 2-1 Typical plan for steel and reinforced concrete special moment-resisting frame (SMRF) archetypes.

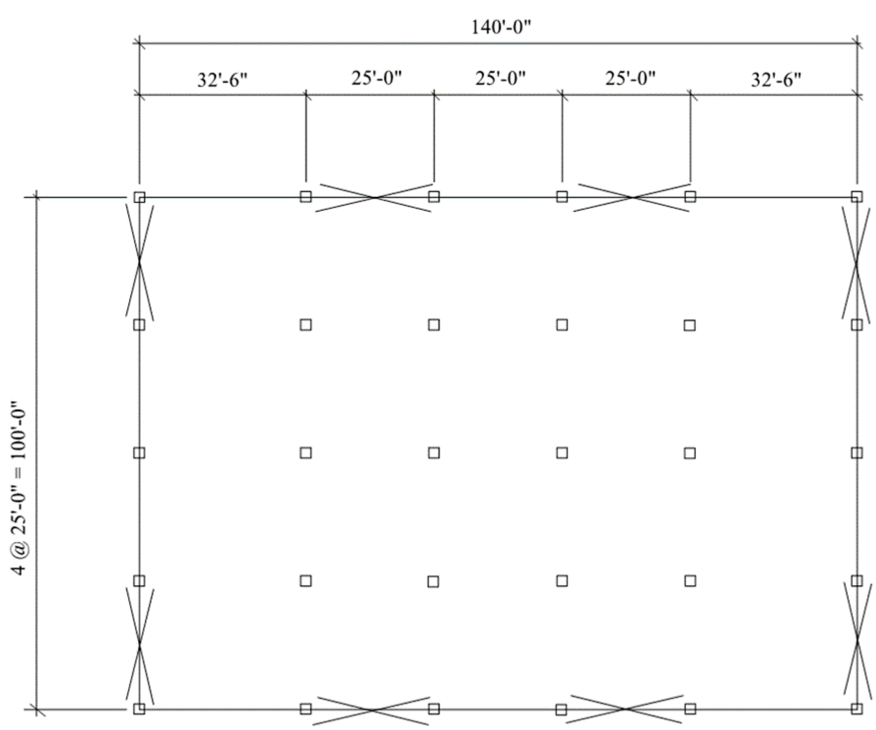


Figure 2-2 Typical plan for steel buckling-restrained braced frame (BRBF) and special concentrically braced frame (SCBF) archetypes.

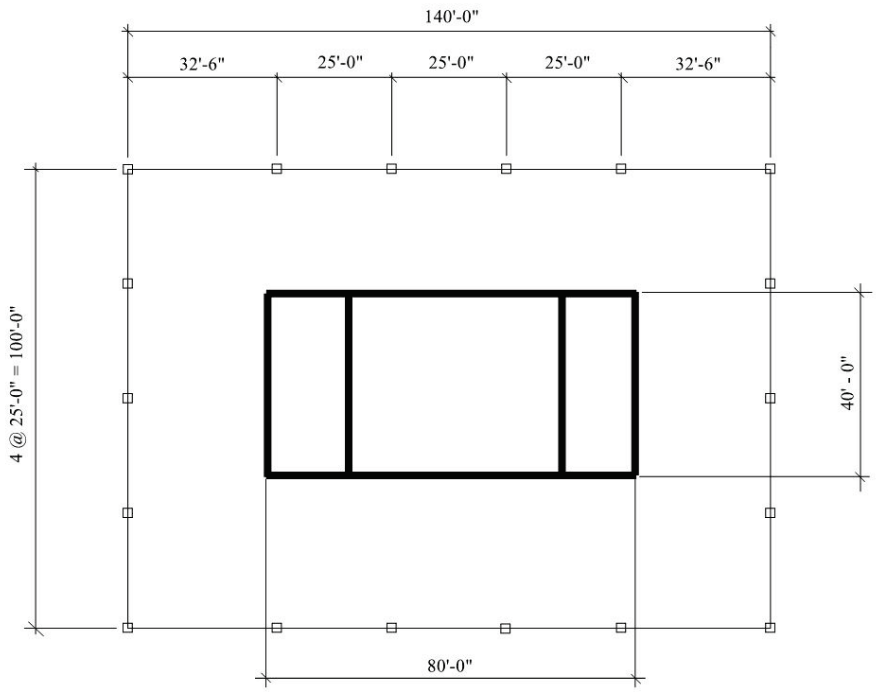


Figure 2-3 Typical plan for special reinforced concrete shear wall (SRCSW) archetypes.

2.3.3 Occupancies and Risk Categories

Building occupancy determines the type and quantity of contents, and the number of people that will be present (and when), within a building. Building occupancy, along with risk and importance, influences the seismic design force level. Risk Categories are a categorization of buildings based on use (or occupancy) and the risk associated with unacceptable performance. Risk Categories are used to reduce permissible story drifts, trigger increased construction quality assurance requirements, and assign importance factors that increase seismic design loading. Buildings and other structures that represent a low risk to human life are assigned Risk Category I; standard occupancy structures are assigned Risk Category II; hazardous or otherwise important facilities are assigned Risk Category III; and essential facilities are assigned Risk Category IV.

Two types of occupancies were considered in this study: office and healthcare. Office and healthcare occupancies were each designed as standard occupancy (Risk Category II) and essential (Risk Category IV) structures, as follows:

- Office archetypes in Risk Category II representing standard commercial office buildings.
- Office archetypes in Risk Category IV representing an emergency operations center or other essential facility, with contents and occupancy similar to an office environment.
- Healthcare archetypes in Risk Category II representing medical buildings that perform outpatient diagnostic imaging and outpatient surgical services, in which patients stay less than 24 hours.
- Healthcare archetypes in Risk Category IV representing general acute-care hospital buildings that provide in-patient surgical, imaging, and laboratory services, in which patients stay more than 24 hours.

Office and healthcare occupancies differ in terms of the number of people and times when people are assumed to be present in the building. Default FEMA P-58 population models for office and healthcare occupancies were used. Office occupancies assume people are present during business hours, with limited occupancy during off hours and weekends. Healthcare occupancies assume essentially continuous (24-hour) occupancy, seven days per week.

Office and healthcare occupancies also differ in the types and quantities of nonstructural components and systems assumed to be present in the building. In addition to architectural, mechanical, electrical, and plumbing components in office archetypes, healthcare archetypes are populated with representative fixed and mobile medical equipment typically found in acute care hospitals.

Risk Category II structures were designed with a seismic importance factor of 1.0, and Risk Category IV structures were designed with a seismic importance factor of 1.5. Risk Category II office archetypes include all three height configurations (low-, mid-, and high-rise), while Risk Category IV office, and all healthcare archetypes, were limited to low- and mid-rise configurations only. For a given combination of Risk Category, hazard level, and height configuration, the structural properties of office and healthcare archetypes are identical.

2.3.4 Seismic Hazard Levels

Seismic Design Category (SDC) is a classification assigned to a structure based on its Risk Category and the severity of the design earthquake ground motions at the site. Design ground motion intensity is determined by the site location and the characteristics of the underlying soil.

Archetypes have been located in three seismic settings, all considered to be regions of high seismicity. Locations were selected with mapped spectral response acceleration parameters resulting in design values corresponding to three seismic hazard levels: Low SDC D (just above the SDC C/D boundary), SDC D, and SDC E/F (near active faults). Default Site Class D was assumed for all sites.

Table 2-3 summarizes short-period mapped spectral response acceleration parameters, site coefficients, maximum considered earthquake parameters, and design parameters associated with each seismic hazard level. Table 2-4 summarizes the same information at 1-second period for each hazard level. Design response spectra corresponding to these parameters are shown in Figure 2-4.

Table 2-3 Short-Period Spectral Response Acceleration Parameters Associated with each Seismic Hazard Level

Site Seismic Hazard Level	Maximum Considered Earthquake[1]			Design Earthquake
	S_S	F_a [2]	S_{MS}	S_{DS}
SDC E/F [3]	2.0g	1.0	2.0g	1.33g
SDC D	1.5g	1.0	1.5g	1.0g
Low SDC D	0.55g	1.36	0.75g	0.50g

Notes: [1] Risk-targeted Maximum Considered Earthquake (MCE_R).
[2] Liner interpolation is used for intermediate values of S_S.
[3] Seismic Design Category is SDC E for Risk Category II archetypes and SDC F for Risk Category IV archetypes.

Table 2-4 1-Second Period Spectral Response Acceleration Parameters Associated with each Seismic Hazard Level

Site Seismic Hazard Level	Maximum Considered Earthquake[1]			Design Earthquake
	S_1	F_v [2]	S_{M1}	S_{D1}
SDC E/F [3]	0.75g	1.5	1.1g	0.75g
SDC D	0.60g	1.5	0.90g	0.60g
Low SDC D	0.29g	1.82	0.53g	0.35g

Notes: [1] Risk-targeted Maximum Considered Earthquake (MCE_R).
[2] Liner interpolation is used for intermediate values of S_1.
[3] Seismic Design Category is SDC E for Risk Category II archetypes and SDC F for Risk Category IV archetypes.

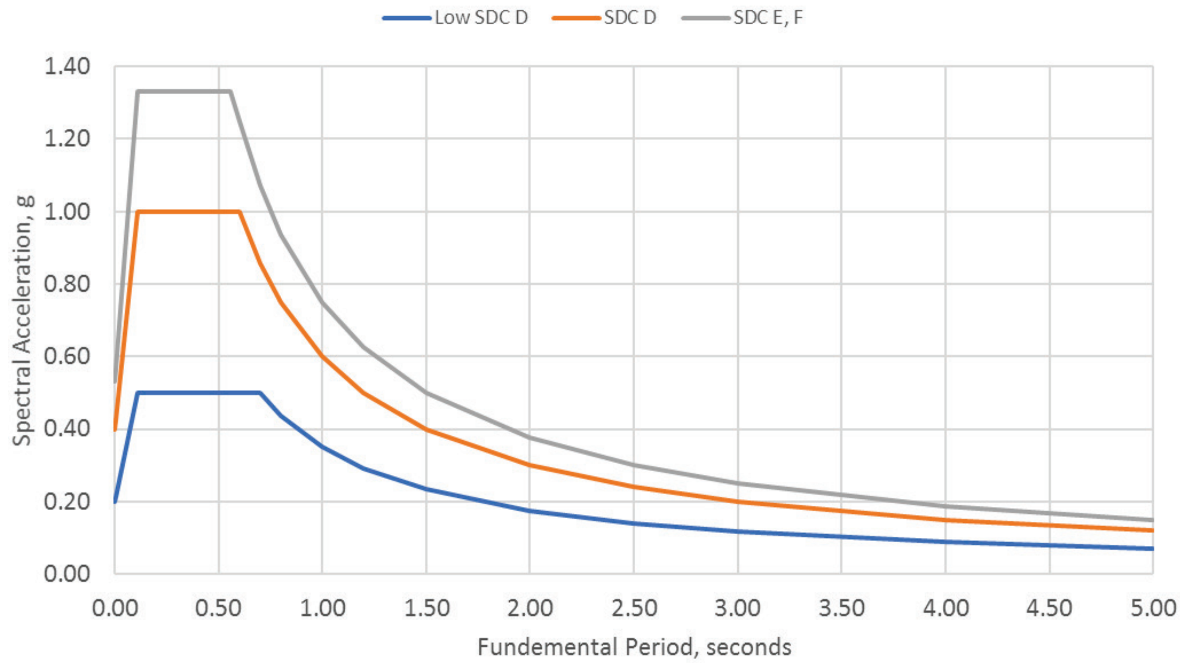


Figure 2-4 Design response spectra for sites corresponding to Low SDC D, SDC D, and SDC E/F hazard levels.

2.3.5 Design Space

All structures must conform to the minimum strength, stiffness, and seismic detailing requirements of the building code. In theory, all buildings could be designed to just meet the minimum base shear strength and maximum allowable drift limits specified for the selected system, configuration, height, and Risk Category. In practice, however, most structures exceed code minimums in one way or another, and for a variety of reasons.

Practical constraints on the combinations of lateral strength and stiffness for different seismic force-resisting systems can result in buildings that are stronger or stiffer than required. For example, steel special moment-resisting frames are typically governed by story drift limits, but the actual strength of frames with the required stiffness often significantly exceeds the code design base shear. Conversely, steel braced frame systems are typically governed by strength requirements, but braced frames are often stiffer than the minimum stiffness required, and actual drifts are far less than code allowable drift limits.

Practical constraints on building configuration can result in the presence of more structure than would otherwise be required. For example, in the case of shear wall buildings, the need for a complete building envelope can result in additional concrete, masonry, or light-frame shear walls that provide more lateral strength and stiffness than would be needed based on seismic design considerations alone.

Structural engineers can also make a conscious decision to provide a structure that is stronger or stiffer than required. This can be the result of individual design bias, office design standards, or conventional design practices. It can also be the result of practical constraints dictated by the building configuration, foundation requirements, or other controlling design or construction considerations (e.g., cost, schedule, or ease of construction).

For these reasons, 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 seismic design requirements. Seismic requirements, however, only specify the minimum strength and maximum allowable drift boundaries of the design space. Assumptions for upper-bound strength and lower-bound drift limits were needed to complete the design space.

Because designs that exceed code minimums are not controlled by code requirements, the possible range of designs is theoretically infinite. To determine a set of reasonable bounds on strength and stiffness, a workshop was convened to gain insight from practicing structural engineers on typical characteristics associated with code-conforming seismic force-resisting systems. In this workshop, engineers from multiple design firms, in diverse areas of seismic design practice, were asked to provide guidance on the probable range of strength and stiffness, relative to code-specified minimums, that code-conforming buildings might have, given other factors.

Findings from this workshop are presented in ATC-58-5, *Proceedings of FEMA-Sponsored Workshop on Design Guidelines and Tools to Implement Next-Generation Performance-Based Seismic Design* (ATC, 2014), and the resulting recommendations were used to establish the design space for each system in this study. The following guiding principles were taken from workshop discussions:

- Drift-controlled systems (e.g., moment-resisting frames) are designed to drift limits that are less than or equal to code limits, but actual strengths will be significantly higher than the minimum design base shear.
- Strength-controlled systems (e.g., shear walls and braced frames) are much stiffer than required, and cannot practically reach maximum allowable drift limits.

- Although it can be higher in certain special cases, a reasonable upper-bound lateral strength for typical structures is approximately two to three times the design base shear.

A typical design space is shown in Figure 2-5, which illustrates typical upper and lower bound assumptions for strength and stiffness. 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. Thirteen points are used to characterize archetypes with different strength and stiffness combinations throughout the design space.

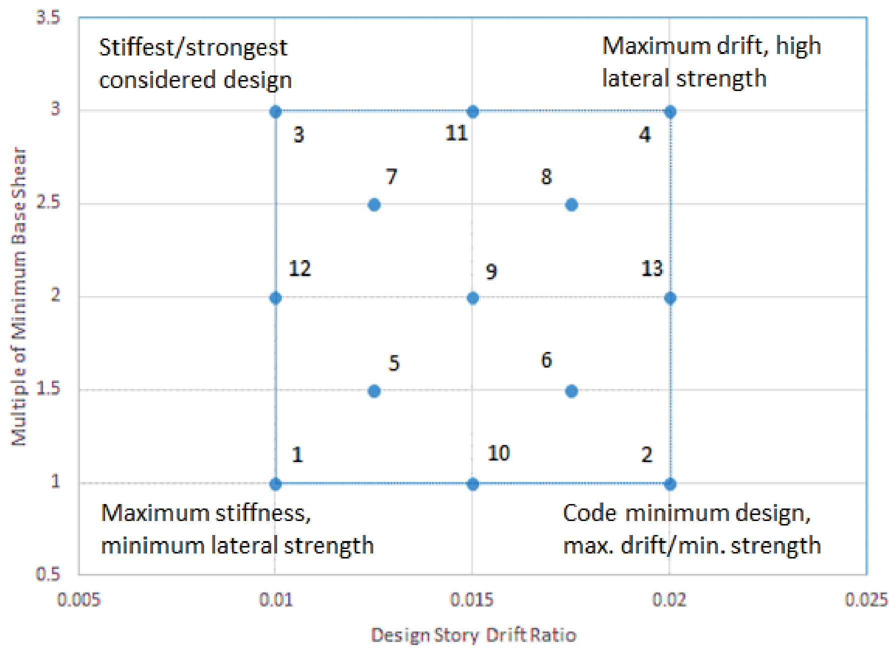


Figure 2-5 Typical design space showing 13 points used to characterize different strength and stiffness combinations for each archetype.

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 the minimum permitted lateral strength. Point 2 represents the theoretical code-minimum design, which is a structure having the maximum practical design story drift ratio and the 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. Different systems have different upper and lower bound assumptions for strength and stiffness. Limits for the design space of each system are summarized in Table 2-5 and Table 2-6.

Table 2-5 Design Space Limits for Lateral Strength and Stiffness, Risk Category II Archetypes

Seismic Force-Resisting System	Maximum Strength (Multiple of Code Design Base Shear)	Minimum Drift Ratio (%)	Maximum Drift Ratio (%)	Code Maximum Allowable Drift Ratio (%)
Low-Rise Archetypes				
Steel SMRF	3.0	1%	2.5%	2.5%
RC SMRF	2.0	1%	2.5%	2.5%
Steel BRBF	2.0	0.5%	1.5%	2.5%
Steel SCBF	2.0	0.25%	1.25%	2.5%
Special RCSW	3.0	0.25%	1%	2.5%
Mid-Rise / High-Rise Archetypes(1)				
Steel SMRF	3.0	1%	2%	2%
RC SMRF	2.0	1%	2%	2%
Steel BRBF	2.0	0.5%	1.5% / 2%	2%
Steel SCBF	2.0	0.25% / 0.5%	1.25% / 2%	2%
Special RCSW	3.0	0.25% / 0.5%	1% / 2%	2%

Notes: (1) Where two values are shown, mid-rise and high-rise variants have different limits.

Table 2-6 Design Space Limits for Lateral Strength and Stiffness, Risk Category IV Archetypes

Seismic Force-Resisting System	Maximum Strength (Multiple of Code Design Base Shear)	Minimum Drift Ratio (%)	Maximum Drift Ratio (%)	Code Maximum Allowable Drift Ratio (%)
Low-Rise Archetypes				
Steel SMRF	3.0	1%	1.5%	1.5%
RC SMRF	2.0	1%	1.5%	1.5%
Steel BRBF	2.0	0.5%	1.5%	1.5%
Steel SCBF	2.0	0.25%	1%	1.5%
Special RCSW	3.0	0.25%	1%	1.5%
Mid-Rise Archetypes(1)				
Steel SMRF	3.0	0.5%	1%	1%
RC SMRF	2.0	0.5%	1%	1%
Steel BRBF	2.0	0.5%	1%	1%
Steel SCBF	2.0	0.25%	1%	1%
Special RCSW	3.0	0.25%	1%	1%

Notes: (1) Risk Category IV archetypes do not have high-rise variants.

The resulting design space for each system varies based on Risk Category, building height, and bounding assumptions for strength and stiffness that can differ from code limits, especially in the case of allowable drift ratios. Design space limits, where they differ from the code, have been determined based on workshop input and engineering judgment. For example, moment-resisting frame archetypes use code maximum allowable drift ratios as an upper limit, while stiffer braced frame and shear wall archetypes have an assumed upper limit that is much smaller than code allowable drift ratios. Maximum strengths for each system have been taken as two or three times the code design base shear. Other points distributed along the perimeter and interior of the design space are used to measure how performance is affected by variations in lateral strength and stiffness.

2.3.6 Representative Designs

The parametric variation of strength and stiffness within the design space includes combinations of lateral strength and stiffness that might not be realistic for some systems. However, all points within the boundaries of the design space are considered necessary to characterize the performance of the range of parameters considered to be code-conforming for each system.

To quantify performance for a subset of the design space that is considered most representative of typical design practice, the concept of a representative design was developed. *Representative designs* are combinations of lateral strength and lateral stiffness that are judged to be most typical for each seismic force-resisting system, including consideration of whether the system is typically strength-controlled or drift-controlled.

The combination of strength and stiffness judged to be most representative of each system is not necessarily one of the 13 points in the design space. It is generally taken as an average of three or four points closest to the region of the design space considered to be most typical for design of the system in engineering practice. For comparison, representative design points for each system are plotted within a generic design space in Figure 2-6.

The generic design space in Figure 2-6, however, is not representative of any one design space. It is intended to illustrate the relative differences between representative designs across all systems. The actual dimensions of the design space and the properties associated with representative designs are calculated uniquely for each system and summarized in Tables 2-7 and 2-8. A comparison between actual design space limits and representative design points for mid-rise, Risk Category II, steel special moment-resisting frame and buckling-restrained braced frame systems is shown in Figure 2-7.

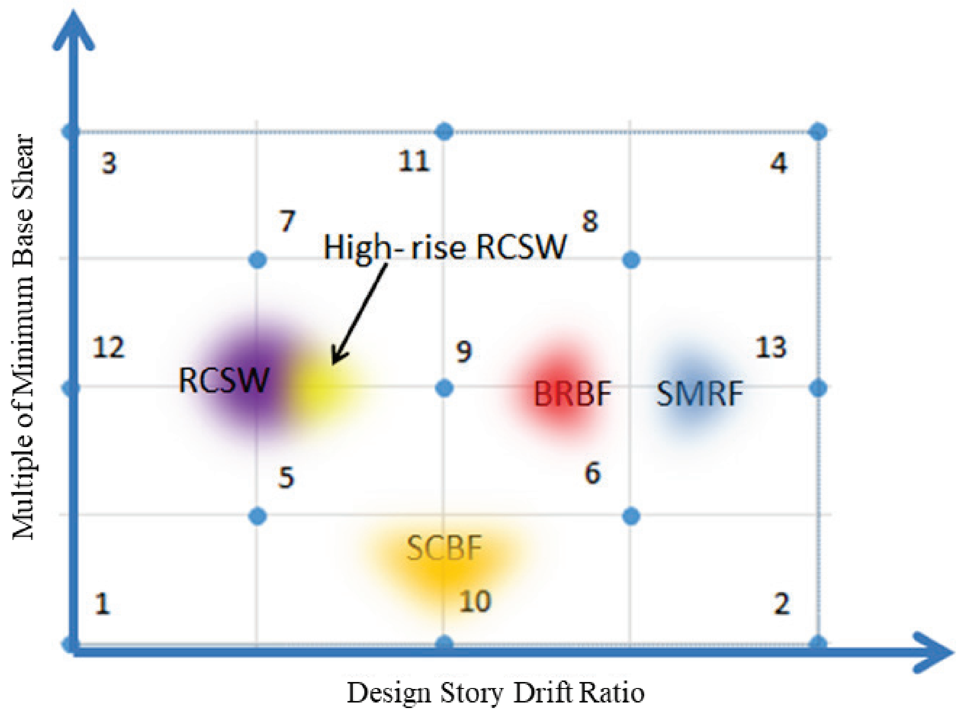


Figure 2-6 Plot of representative design points for each seismic force-resisting system in a generic design space.

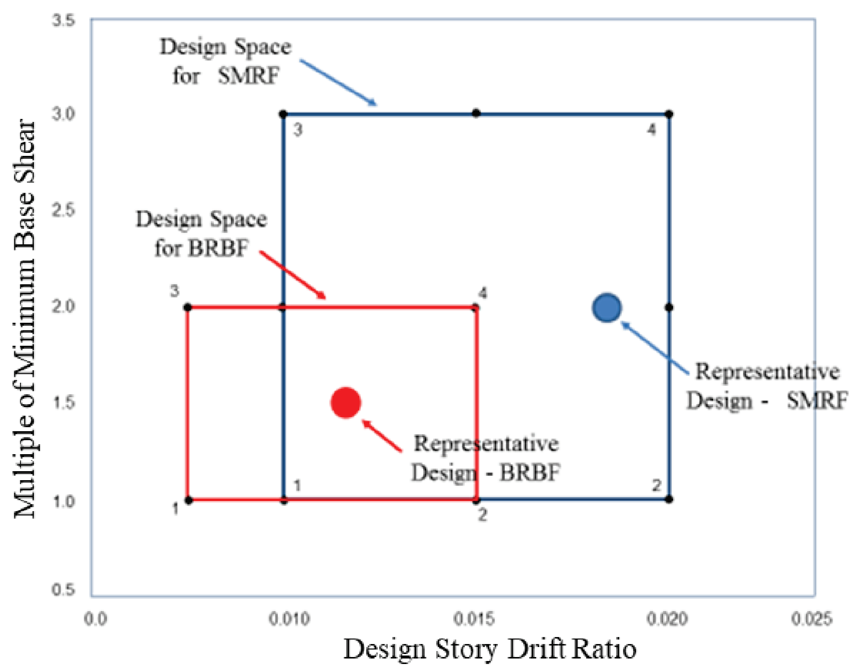


Figure 2-7 Comparison of design space limits and representative design points for mid-rise, Risk Category II, Steel SMRF and BRBF archetypes.

Table 2-7 Lateral Strength and Drift Ratios for Representative Designs, Risk Category II Archetypes

Seismic Force-Resisting System	Strength (Multiple of Code Minimum Design Base Shear)	Drift Ratio (%)
Low-Rise Archetypes		
Steel SMRF	2.0	2.25%
RC SMRF	1.5	2.25%
Steel BRBF	1.5	1.17%
Steel SCBF	1.125	0.75%
Special RCSW	2.0	0.44%
Mid-Rise / High-Rise Archetypes		
Steel SMRF	2.0	1.8%
RC SMRF	1.5	1.8%
Steel BRBF	1.5	1.17% / 1.5%
Steel SCBF	1.125	0.75% / 1.25%
Special RCSW	2.0	0.44% / 1.0%

Table 2-8 Lateral Strength and Drift Ratios for Representative Designs, Risk Category IV Archetypes

Seismic Force-Resisting System	Strength (Multiple of Code Minimum Design Base Shear)	Drift Ratio (%)
Low-Rise Archetypes		
Steel SMRF	2.0	1.4%
RC SMRF	1.5	1.4%
Steel BRBF	1.5	1.17%
Steel SCBF	1.125	0.63%
Special RCSW	2.0	0.44%
Mid-Rise Archetypes(1)		
Steel SMRF	2.0	0.9%
RC SMRF	1.5	0.9%
Steel BRBF	1.5	0.83%
Steel SCBF	1.125	0.63%
Special RCSW	2.0	0.44%

Notes: (1) Risk Category IV archetypes do not have high-rise variants.

2.3.7 Summary of Building Archetypes

Archetypes are defined by lateral system type, height, lateral strength, lateral stiffness, occupancy, and design ground motion. Archetypes were designed for five different seismic force-resisting systems, two Risk Categories, and three levels of seismic hazard. Table 2-9 summarizes the combinations of occupancies, seismic force-resisting systems, Risk Categories, and building heights included in the archetype parametric studies.

For each combination of occupancy, Risk Category, and building height, archetypes were created at each of three levels of seismic hazard, for each of the 13 combinations of lateral strength and stiffness representing the design space. Each system is, therefore, represented by a combination of 195 office and 156 healthcare archetypes (351 total archetypes per system), for a total of 1,755 archetypes across all five seismic force-resisting systems.

Table 2-9 Summary of Archetypes by Occupancy, System, Risk Category, and Building Height

Occupancy	Seismic Force-Resisting System	Risk Category	2-Story	3-Story	5-Story	12-Story
Office (975 archetypes)	Steel SMRF (195 archetypes)	II		■	■	■
		IV		■	■	
	RC SMRF (195 archetypes)	II		■	■	■
		IV		■	■	
	Steel BRBF (195 archetypes)	II	■		■	■
		IV	■		■	
	Steel SCBF (195 archetypes)	II	■		■	■
		IV	■		■	
	Special RCSW (195 archetypes)	II	■		■	■
		IV	■		■	
Healthcare (780 archetypes)	Steel SMRF (156 archetypes)	II		■	■	
		IV		■	■	
	RC SMRF (156 archetypes)	II		■	■	
		IV		■	■	
	Steel BRBF (156 archetypes)	II	■		■	
		IV	■		■	
	Steel SCBF (156 archetypes)	II	■		■	
		IV	■		■	
	Special RCSW (156 archetypes)	II	■		■	
		IV	■		■	

2.4 Simplified Structural Design and Analysis

Because of the large number of archetypes considered, a simplified design and analysis approach was used to determine structural properties associated with each archetype, and to estimate structural response quantities (drifts, accelerations, and velocities) for performance assessment.

Structural properties were determined for each point in the design space by equating code-based strength and period calculations to the strength and drift limits associated with the design point under consideration. Structural demands were calculated using the simplified analysis procedure in FEMA P-58, Volume 1. The determination of structural properties (strength, stiffness, period) and demand quantities (drift, acceleration, and velocity) is described in Chapter 3.

2.5 Building Performance Models

For each archetype, a PACT building performance model was created that includes project information, building information, population data, component structural and nonstructural fragilities, performance groups, collapse fragilities, structural analysis results (drift, acceleration, and velocity), residual drift information, and hazard curves. Assembly of the building performance models is described in Chapter 4.

For a given a seismic force-resisting system, hazard level, building height, Risk Category, and point on the design space, the structural portion of the PACT performance models for office and healthcare occupancies are identical. Nonstructural performance models vary with occupancy, and include more variation based on design story drift and location of nonstructural components over the height of the structure. Nonstructural models were assembled separately and subsequently combined with the appropriate structural portion of the model for performance assessment of each archetype.

2.5.1 Selection of Structural and Nonstructural Fragilities

For each seismic force-resisting system, structural fragilities were selected from the PACT fragility database that best characterize typical structural components found in each system. Typical nonstructural fragilities were selected based on information from the *Normative Quantity Estimation Tool* in FEMA P-58, Volume 3. Custom fragilities for medical equipment were developed for the purposes of this study. Selection of structural and nonstructural fragilities is described in Chapter 4.

2.6 Limitations

The FEMA P-58 methodology employs analysis techniques that characterize building performance metrics in a probabilistic manner, recognizing the many uncertainties that can affect building performance. Results for each metric are provided in the form of a probability distribution, and performance metrics at any confidence level can be reported. In this study, median results are presented. Median values provide the expected performance in the middle of the distribution, with half of the possible values higher, and half of the possible values lower than the reported value. In some circumstances a higher confidence level may be appropriate, such as the 90th percentile value, which would provide a higher confidence that the reported performance metric will not be exceeded.

Properties of the structural seismic force-resisting systems and nonstructural component seismic bracing and anchorage were proportioned to comply with the seismic provisions of ASCE/SEI 7-10. Structural members and connections are assumed to comply with the requirements in ANSI/AISC 360, *Specification for Structural Steel Buildings* (AISC, 2010b), ANSI/AISC 341-10, S*eismic Provisions for Structural Steel Buildings* (AISC, 2010a), and ACI 318-11, *Building Code Requirements for Structural Concrete and Commentary* (ACI, 2011). The performance evaluations presented herein apply only to buildings that fully comply with all structural and nonstructural seismic design requirements in ASCE/SEI 7-10 and applicable material design standards.

The possibility of building collapse was included in the performance assessments in an approximate manner. A fundamental assumption in this study is that life safety performance, as measured by an acceptably low probability of collapse, is achieved by designing and constructing buildings in accordance with the requirements in ASCE/SEI 7-10. Collapse fragilities were developed using a modified version of the judgment-based procedure in FEMA P-58, Volume 1, Section 6.4, which is based on a 10 percent probability of collapse for standard occupancy structures, given the occurrence of maximum considered earthquake shaking. A lower (i.e., 5 percent) collapse probability was assumed for the structures represented by the design space in this study, based on the rationale provided in Chapter 3.

Foundation elements were not included in the performance models. For some seismic force-resisting systems, foundations may be vulnerable to damage that has not been considered in this study.

Quantities of nonstructural components and systems were developed using the *Normative Quantity Estimation Tool* in FEMA P-58, Volume 3. Components deemed rugged (i.e., not subject to significant damage for credible levels of seismic demand) in FEMA P-58, Volume 1, were excluded from the performance models. Building contents, such as furniture and electronic equipment (not designated as medical equipment) were also excluded from the performance models because they are not permanently attached to the structure, and are, therefore, exempt from the seismic provisions of the building code.

Healthcare occupancy performance models include judgement-based fragilities for fixed and mobile medical components developed specifically for this study, as described in Chapter 4. Median capacities for medical components were determined based on the seismic design forces required by ASCE/SEI 7-10 and the procedures for calculation-based fragilities in FEMA P-58, Volume 1. Repair costs and repair times are rough order-of-magnitude, judgement-based estimates that consider component cost and perceived complexity. Repair costs consider only the cost of the component, and do not include any ancillary work required to access or reinstall the damaged component. Mobile components (i.e., components commonly installed on rollers for easy transport) are velocity-controlled. Median capacities were based on assumptions of how far a component can move before it impacts another component and becomes damaged.

Performance estimates for healthcare occupancies are intended for study of the potential influence of design decisions, especially Risk Category, on performance. Because of the diverse nature of healthcare facilities, and the approximate nature of the assumed medical component fragilities, the resulting performance estimates should be considered as lower-bound, and used for comparative purposes only.

Chapter 3
Structural Properties

Because of the large number of archetypes considered in this study, a simplified design and analysis approach was used to determine structural properties associated with each archetype, and to estimate structural response quantities (drifts, accelerations, and velocities) for performance assessment. This information is necessary for sizing structural components, and selecting structural and nonstructural fragilities assigned in the building performance models.

3.1 Simplified Design and Analysis Approach

The simplified design approach equates code-based strength and period equations to strength and drift limits that are associated with each point in the design space. The analysis approach utilizes the simplified analysis procedure in FEMA P-58, Volume 1 to calculate pseudo lateral forces and estimate drift, acceleration, and velocity response quantities.

The structural properties of each archetype were assumed to be identical in each orthogonal direction. All archetypes were assumed to be regular and redundant, with mass uniformly distributed over the height, and without the presence of plan or vertical irregularities. Diaphragms were assumed to be rigid, and torsion and foundation flexibility were ignored. Determination of structural properties and estimation of response quantities for each archetype at each point in the design space included the following steps:

- Archetype selection and identification
- Estimation of dynamic properties
- Calculation of code-minimum strength
- Estimation of yield strength and yield drift
- Determination of collapse fragility
- Estimation of structural demands

3.2 Archetype Selection and Identification

Archetypes are identified by seismic force-resisting system, occupancy, risk category, hazard level, and building height. For each combination of the above parameters, archetypes were designed for the lateral strength and stiffness represented by each of the 13 points comprising the design space.

Systems were selected from those identified in Table 3-1, along with the response modification coefficient, R, the system overstrength factor, Ω_0, and deflection amplification factor, C_d, from ASCE/SEI 7-10, Table 12.2-1.

Table 3-1 Seismic Force-Resisting Systems and Seismic Design Coefficients

Seismic Force-Resisting System	Response Modification Coefficient, R	System Overstrength Factor, Ω_0	Deflection Amplification Factor, C_d
Steel SMRF	8	3	5.5
RC SMRF	8	3	5.5
Steel BRBF	8	2.5	5
Steel SCBF	6	2	5
Special RCSW	6	2.5	5

The site seismic hazard level was selected from Table 3-2, which summarizes the short-period, S_{DS}, and 1-second period, S_{D1}, design values at each level.

Table 3-2 Design Parameters at Each Seismic Hazard Level

Site Seismic Hazard Level	S_{DS}	S_{D1}
SDC E/F (1)	1.33g	0.75g
SDC D	1.00g	0.6g
Low SDC D	0.50g	0.35g

Notes: (1) Seismic Design Category is SDC E for Risk Category II archetypes and SDC F for Risk Category IV archetypes.

Upper-bound values of strength for each system were determined based on input from ATC-58-5 workshop proceedings (ATC, 2014) and judgment. Multiples of minimum design strength used to determine the upper bound strength for the design space of each system are summarized in Table 3-3.

Table 3-3 Upper-Bound Design Strengths

Seismic Force-Resisting System	Multiple of ASCE/SEI 7-10 Minimum Design Base Shear Strength
Steel SMRF	3.0
RC SMRF	2.0
Steel BRBF	2.0
Steel SCBF	2.0
Special RCSW	3.0

Lateral stiffness was determined based on story drift. For drift-controlled systems, upper-bound values for story drift were taken as the maximum allowable value from ASCE/SEI 7-10, Table 12.12-1. For upper-bound drift ratios in strength-controlled systems, and for lower-bound drift ratios in all systems, drift ratio limits were based on input from the ATC-58-5 workshop proceedings (ATC, 2014) and judgment. Values assumed for upper- and lower-bound drift ratios for different systems, risk categories, and building heights are summarized in Table 3-4.

Table 3-4 Upper-and Lower-Bound Design Drift Ratios

Seismic Force-Resisting System	Risk Category	2- and 3- Story		5-Story		12-Story	
		Lower-Bound Drift Ratio	Upper-Bound Drift Ratio	Lower-Bound Drift Ratio	Upper-Bound Drift Ratio	Lower-Bound Drift Ratio	Upper-Bound Drift Ratio
Steel SMRF	II	0.01	0.025	0.01	0.02	0.01	0.02
	IV	0.01	0.015	0.005	0.01		
RC SMRF	II	0.01	0.025	0.01	0.02	0.01	0.02
	IV	0.01	0.015	0.005	0.01		
Steel BRBF	II	0.005	0.015	0.005	0.015	0.005	0.02
	IV	0.005	0.015	0.005	0.01		
Steel SCBF	II	0.0025	0.0125	0.0025	0.0125	0.005	0.02
	IV	0.0025	0.01	0.0025	0.01		
Special RCSW	II	0.0025	0.01	0.0025	0.01	0.005	0.02
	IV	0.0025	0.01	0.0025	0.01		

3.3 Estimation of Dynamic Properties

Dynamic properties for each archetype were determined based on the design story drift at the point of interest in the design space, using an approximate procedure for estimating mode shape and Rayleigh's method for estimating period.

3.3.1 Mode Shape

First mode shapes, ϕ_{j1}, for each archetype were estimated using an approximate method presented in Miranda and Taghavi (2005). In this procedure, buildings are modeled as an equivalent continuum structure consisting of a flexural cantilever beam and shear cantilever beam pin-connected by axially rigid links. Estimated mode shapes are functions of the total height of the building and structural stiffness parameters α and δ, which control the response of the structure. Value of α represent variations in the behavior of the structure from a pure flexural response ($\alpha = 0$), to a pure shear response ($\alpha = 30$). Value of δ represent variations in lateral stiffness over the height of the structure from uniform stiffness ($\delta = 1.0$), to a 50 percent reduction in lateral stiffness between the base and the top of the structure ($\delta = 0.5$).

Values of structural stiffness parameters used to estimate first mode shapes for each archetype are different for different combinations of building height and seismic force-resisting system. Selected values of α and δ are summarized in Table 3-5 by system and building height. Assumed values were determined by calibrating estimated first mode shapes to mode shapes obtained in two-dimensional structural analyses conducted on a series of typical building models for selected systems. The resulting values indicate that responses were assumed to be flexurally dominated, low-rise archetypes were assumed to have a uniform stiffness over height, and mid- and high-rise archetypes were assumed to have a 50% reduction in stiffness over height.

Table 3-5 Structural Stiffness Parameters Used to Estimate First Mode Shape

Seismic Force-Resisting System	Stiffness Parameter	2-story, 3-story	5-story	12-story
Steel SMRF	α	4	6	6
	δ	1.0	0.5	0.5
RC SMRF	α	4	6	6
	δ	1.0	0.5	0.5
Steel BRBF	α	4	6	3
	δ	1.0	0.5	0.5
Steel SCBF	α	4	4	2
	δ	1.0	0.5	0.5
Special RCSW	α	1	2	2
	δ	1.0	0.5	0.5

3.3.2 Fundamental Period

Given the seismic force-resisting system, building height, and hazard level, the bare-frame fundamental period, $T_{1,BF}$, was calculated such that the maximum story drift is equal to the design drift at the point of interest in the design space. Story drift profiles were developed using code lateral forces and the target drift ratio, and the bare-frame fundamental period corresponding to the design drift was determined using Rayleigh's method in an iterative procedure.

To obtain lateral deflections, δ_x, the first mode shape was computed using Miranda and Taghavi (2005). The amplitudes of the fundamental mode shape, $\phi_1(x)$, were scaled so that the story drift at the floor with the highest drift demand equals the design story drift. The deflection used to compute story drift, δ_x, at level x, was determined using ASCE/SEI 7-10 Equation 12.8-15:

$$\delta_x = \frac{C_d \delta_{xe}}{I_e}$$

where C_d is the deflection amplification factor in ASCE/SEI 7-10, δ_{xe} is the elastic deflection at level x due to strength-level design earthquake forces, F_x, distributed along the building height, and I_e is the importance factor. The largest value of δ_x should equate to the design story drift ratio at the point of interest in the design space.

Because the magnitude of the forces, f_x, used in the Rayleigh method are a function of period, an initial estimate of period is needed. For the first iteration, the code upper limit on period, T_{max}, was used:

$$T_{max} = C_u T_a$$

where T_a is the approximate fundamental period per ASCE/SEI 7-10, Equation 12.8-7, and C_u is the coefficient for the upper limit on calculated period per ASCE/SEI 7-10, Table 12.8-1. Based on this period, the forces, f_x, were calculated. The lateral force, f_x, that corresponds to lateral deflection, δ_x, at level x, is:

$$f_x = \frac{C_d F_x}{I_e}$$

where the equivalent seismic force, F_x, at each level is determined by ASCE/SEI 7-10, Equation 12.8-11 and Equation 12.8-12:

$$F_x = C_{vx} V$$

$$C_{vx} = \frac{w_x h_x^k}{\sum_{i=1}^{n} w_i h_i^k}$$

where V is the seismic base shear, w_i and w_x are the portions of the total effective seismic weight of the structure (W) located or assigned to level i or x, and h_i and h_x is the height (in feet) from the base to level i or x. Because the mass distribution of the building is assumed to be uniform, $w_x = w_i = W/N$, where N is the number of stories. Coefficient, k, is a number that defines the shape of the equivalent lateral force pattern, and depends on the period of the structure. For structures with a period of 0.5 s or less, $k = 1$; for structures with a period of 2.5 s or more, $k = 2$; and for structures with a period between 0.5 s and 2.5 s, k is determined by linear interpolation between 1 and 2.

The seismic design base shear V was calculated using ASCE/SEI 7-10, Equation 12.8-1:

$$V = C_s W$$

where C_s is the seismic response coefficient calculated per ASCE/SEI 7-10, Equation 12.8-2:

$$C_S = \frac{S_{DS}}{R/I_e}$$

The value of C_s need not exceed the limits given by ASCE/SEI 7-10, Equation 12.8-3 and Equation 12.8-4:

$$C_S = \frac{S_{D1}}{T\left(R/I_e\right)} \quad \text{for } T \leq T_L$$

$$C_S = \frac{S_{D1}T_L}{T^2\left(R/I_e\right)} \quad \text{for } T > T_L$$

If S_1 is greater than or equal to 0.6g, then C_s shall not be less than the limit given by ASCE/SEI 7-10, Equation 12.8-6:

$$C_S = 0.5\frac{S_1}{R/I_e}$$

ASCE/SEI 7-10, Section 12.8.6.1 states that ASCE/SEI 7-10, Equation 12.8-5 need not be considered when computing drift.

Forces, f_x, were then used to calculate a new estimate of period, $T_{computed}$. The fundamental circular frequency and the corresponding period using Rayleigh's method are:

$$\omega_{computed} = \sqrt{\frac{g\sum_{x=1}^{n}\delta_x f_x}{\sum_{x=1}^{n}\delta_x^2 w_x}}$$

$$T_{computed} = \frac{2\pi}{\omega_{computed}}$$

where g is the gravitational constant, w_x is the portion of the total effective seismic weight of the structure (W) located or assigned to level x, δ_x is the lateral deflection at level x, and f_x is the corresponding lateral force at level x.

The values of initial estimated period, T, and the period estimated using Rayleigh's method, $T_{computed}$, were compared in an iterative procedure. If $|T - T_{computed}| \leq 0.05$, then the values converged, and the fundamental bare frame period, $T_{1,BF}$, was taken as $T_{computed}$. If not, then $T_{computed}$ was used as the new initial period, and process was repeated until the values converged.

3.3.3 Effective Fundamental Period

The seismic force-resisting system in most new buildings is proportioned using an analytical model that neglects the contributions of gravity framing and nonstructural components on the dynamic response of the structure. When assessing seismic performance, neglecting the contributions of the gravity framing and nonstructural components to stiffness will result in an over-prediction of drift demands.

In the FEMA P-58 methodology, analytical models of buildings should include all elements that contribute to lateral strength or stiffness. In this study, the fundamental bare frame period, $T_{1,BF}$, was modified to reflect the period stiffening effects associated with the presence of gravity framing and nonstructural components that contribute to lateral stiffness.

The effective fundamental period, $T_{1,EFF}$, is given by:

$$T_{1,EFF} = (MF)T_{1,BF}$$

where values of the modification factor, MF, for different systems are summarized in Table 3-6. Period modification factors, MF, are based on comparisons between computed and measured fundamental periods in instrumented buildings described in Harris, et al., 2016 (FEMA P-58/BD-3.7.17 Report).

Table 3-6 Period Modification Factor, *MF*, by System

Seismic Force-Resisting System	Period Modification Factor, *MF*
Steel SMRF	0.55
RC SMRF	0.85
Steel BRBF	0.85
Steel SCBF	0.85
Special RCSW	0.9

3.4 Code Minimum Base Shear Strength

The code minimum base shear strength, V_b, was computed based on ASCE/SEI 7-10, Equation 12.8-1:

$$V_b = C_s W$$

where:

$$C_S = \frac{S_{DS}}{R/I_e}$$

and I_e is the importance factor, R is the response modification coefficient, and W is the effective seismic weight. The value of C_s need not exceed:

$$\frac{S_a(T_1)}{R/I_e}$$

ASCE/SEI 7-10 places an upper limit on the building period used to calculate the design base shear strength. The upper limit period, T_{max}, is:

$$T_{max} = C_u T_a$$

where T_a is the approximate fundamental period per ASCE/SEI 7-10, Equation 12.8-7 and C_u is the coefficient for upper limit on calculated period. The period used to determine the design base shear strength, T_1, was taken as the lesser of the effective fundamental period, $T_{1,EFF}$, and T_{max}.

The first mode spectral acceleration, $S_a(T_1)$, was determined based on the provisions of ASCE/SEI 7-10, Section 11.4.5, using one of the following equations:

$$S_a(T_1) = S_{DS}\left(0.4 + 0.6\frac{T_1}{T_0}\right) \qquad \text{for } T_1 < T_0$$

$$S_a(T_1) = S_{DS} \qquad \text{for } T_0 < T_1 < T_s$$

$$S_a(T_1) = \frac{S_{D1}}{T_1} \qquad \text{for } T_s < T_1 < T_L$$

where $S_a(T_1)$ is the 5 percent damped spectral acceleration at the lesser of the effective fundamental period, $T_{1,EFF}$, and T_{max}; S_{DS} is the design spectral response acceleration parameter in the short period range; S_{D1} is the design spectral response acceleration parameter at a period of 1.0 sec; and:

$$T_0 = 0.2\frac{S_{D1}}{T_1}$$

$$T_S = \frac{S_{D1}}{S_{DS}}$$

T_L = Long-period transition period

None of the archetypes had periods greater than the long-period transition period, T_L. Because a cap is placed on the fundamental period of a building for strength checks, the design base shear for lateral strength can be larger than the base shear used to check for compliance with story drift limits. The code minimum base shear strength identifies the strength of archetypes along the horizontal line at the bottom of the design space corresponding to a multiple of 1.0. The base shear strength of archetypes at other locations in the design space are a multiple of the code minimum base shear strength.

3.5 Yield Strength

The yield strength, V_y, of a structure can be estimated using plastic analysis concepts, nonlinear analysis in accordance with ASCE/SEI 41-13, *Seismic Evaluation and Retrofit of Existing Buildings* (ASCE, 2017c), or a combination of the response modification coefficient, *R*, and the systems overstrength factor, Ω_0, specified in ASCE/SEI 7-10. In this study, the yield strength was taken as 1.5 times the code minimum base shear strength of the archetype.

The base shear strength of an archetype is a function of the point of interest in the design space, which is a multiple of the code minimum base shear strength, V_b. In this study, the multiple of code minimum base shear at each point in the design space is a form of overstrength, termed the design space overstrength factor, *OF*, and the yield strength is therefore:

$$V_y = 1.5(OF)V_b$$

Upper-bound values for the design space overstrength factor, *OF*, expressed as a multiple of the code minimum base shear strength, are provided in Table 3-3. For the purpose of determining yield strength, values of *OF* for intermediate points in the design space are determined by linear interpolation.

3.6 Yield Drift Ratios

Yield drift ratios for each system were based on parametric and sensitivity studies using approximate methods of analysis, as follows:

- An approximate method of analysis (e.g., portal method for frames) was selected to derive formulas for yield drift in different structural systems.
- Parameters that significantly influence yield drift (e.g., yield strain, ratio of bay span to story height, ratio of column depth to girder depth, ratio of yield stress in columns to yield stress in beams, and aspect ratio of walls) were identified.
- Ranges of probable yield drift were determined by parametric variation of parameters identified as significant.

- Sensitivity studies were conducted on the range of probable yield drift to investigate potential effects on median and 90th percentile losses.
- Yield drift ratios for each system were selected based on the results from sensitivity studies.

3.6.1 Steel Special Moment Resisting Frames

An estimate of the yield drift of steel SMRF archetypes was derived using the portal method of analysis:

$$\Delta_y = \frac{\varepsilon_y}{3}\left(\alpha\frac{h}{d_c} + \frac{L}{d_b}\right)$$

where ε_y is the yield strain of the steel, h is the story height, L is the bay span, d_b is the beam depth, d_c is the column depth, and α is the ratio of the stress in the column to the yield stress in the beam.

To select the yield drift ratio, the yield stress of the steel was varied from 50 ksi to 55 ksi, the bay span to story height ratio (L/h) was varied from 1 to 2, the column depth to beam depth ratio (d_c/d_b) was varied from 0.5 to 0.75, and the ratio of the stress in the column to the yield stress in the beam was varied from 0.7 to 0.8, resulting in a yield drift estimate in the range from 0.8 percent to 1.3 percent. Sensitivity studies showed negligible change in losses with changes in the assumed yield drift ratio. As a result, a yield drift ratio of 1 percent was used for steel SMRF archetypes across the entire design space.

3.6.2 Reinforced Concrete Special Moment-Resisting Frames

An estimate of the yield drift of RC SMRF archetypes was derived using the portal method of analysis:

$$\Delta_y = \frac{\varepsilon_y}{6}\left(\alpha\frac{h}{d_c - kd_c} + \frac{L}{d_b - kd_b}\right)$$

where ε_y is the yield strain of the steel, h is the story height, L is the bay span, d_b is the beam depth, d_c is the column depth, α is the ratio of the stress of the column steel to the yield stress in the beam steel, kd_c is the depth of the neutral axis of the column, and kd_b is the depth of the neutral axis of the beam at yield. The depth of the neutral axis at yield was calculated as:

$$kd = d\left(\sqrt{(n\rho)^2 + 2n\rho} - n\rho\right)$$

where n is the modular ratio $n = (E_s/E_c)$ and ρ is the ratio of longitudinal reinforcement in the element.

To select the yield drift ratio, the bay span to story height ratio (*L*/*h*) was varied from 1 to 2, the column depth to beam depth ratio (d_c/d_b) was varied from 0.67 to 1.0, the ratio of the stress in the column to the yield stress in the beam was varied from 0.7 to 0.8, the ratio of reinforcement in the column was varied from 1 percent to 2 percent, and the ratio of the reinforcement in the steel was varied from 0.8 percent to 1.2 percent, resulting in yield drift estimates in the range from 0.45 percent to 0.65 percent. Sensitivity studies showed negligible change in losses with changes in the assumed yield drift ratio. As a result, a yield drift ratio of 0.55 percent was used for RC SMRF archetypes across the entire design space.

3.6.3 Steel Buckling Restrained Braced Frames

An estimate of the yield drift of steel BRBF archetypes with multistory X-bracing was derived considering a subassembly of a frame including one story level and assuming that the first yield occurs in the brace:

$$\Delta_y = \varepsilon_y \left(\frac{L_2 / 2 + h^2}{hL} \right)$$

where ε_y is the yield strain of the steel, *h* is the story height, and *L* is the bay span.

To select the yield drift ratio, the yield stress of the steel was varied from 38 ksi to 46 ksi, and the bay span to story height ratio (*L*/*h*) was varied from 1.15 to 2.4 to account for possible brace angles between 40 degrees and 60 degrees. The resulting yield drift estimates varied from 0.26 percent to 0.37 percent. A yield drift ratio of 0.30 percent was used for all steel BRBF archetypes across the entire design space.

3.6.4 Steel Special Concentrically-Braced Frames

An estimate of the yield drift of steel SCBF archetypes with multistory X-bracing was derived considering a subassembly of a frame including one story level and assuming that the first yield occurs in the brace:

$$\Delta_y = \varepsilon_y \left(\frac{L_2 / 2 + h^2}{hL} \right)$$

where ε_y is the yield strain of the steel, *h* is the story height, and *L* is the bay span.

To select the yield drift ratio, the yield stress of the steel was varied from 50 ksi to 55 ksi and bay span to story height ratio (*L*/*h*) was varied from 1.15 to 2.4 to account for possible brace angles between 40 degrees and 60 degrees.

The resulting yield drift estimates varied from 0.34 percent to 0.4 percent. Sensitivity studies showed negligible change in losses with changes in the assumed yield drift ratio. As a result, a yield drift ratio of 0.35 percent was selected for steel SCBF archetypes across the entire design space.

3.6.5 *Special Reinforced Concrete Shear Walls*

An estimate of the yield drift of reinforced concrete shear wall archetypes with squat walls (i.e., aspect ratios in the range of 1.5 to 2) was based on experimental data from Tran (2012). An estimate of the yield drift of special RCSW archetypes with slender walls (i.e., aspect ratios greater than 2) was calculated assuming linearly increasing distribution of lateral load and uniform distribution of mass. An estimate of the roof displacement at yield, δ_y, is:

$$\delta_y = \frac{11}{40}\left(\phi_y h_w^2\right)$$

where the curvature at yield, ϕ_y, is approximated as $\varepsilon_y/0.8l_w$, and h_w is the height of the wall, l_w is the length of the wall, and ε_y is the yield strain in the steel bars. With a roof displacement of δ_y, the corresponding displacement at the i^{th} floor level, δ_i, was approximated as:

$$\delta_i = \delta_y \phi_{1,i}$$

where $\phi_{1,i}$ is the value of the fundamental mode shape of the building (normalized to 1 at the roof level) at the i^{th} floor level. Story drifts were calculated from the floor displacements at each story, and the maximum story drift was taken as the yield drift of the archetype. As a result, a yield drift ratio of 0.5 percent was selected for all 2-story RCSW archetypes, 0.26 percent was selected for all 5-story RCSW archetypes, and 0.63 percent was selected for all 12-story RCSW archetypes, across the entire design space.

3.7 Collapse Fragility

The possibility of building collapse was considered through the development of collapse fragilities. In this study, collapse fragilities were developed using a modified version of the judgment-based procedure in FEMA P-58, Volume 1, Section 6.4. The judgement-based collapse fragility is based on the assumption that buildings conforming to the minimum seismic design requirements of Risk Category II structures in ASCE/SEI 7-10 will have a collapse probability of about 10 percent, given the occurrence of maximum considered earthquake shaking at the site.

It has been shown that a 10 percent probability of collapse overpredicts collapse rates observed in past earthquakes, and exceeds collapse rates generally expected to occur in future earthquakes. It has also been shown that buildings exceeding minimum seismic design strength requirements generally exhibit lower collapse probabilities. Because the code minimum design strength represents one boundary of the design space, and the rest of the design space exceeds the code minimum strength, a lower (i.e., 5 percent) collapse probability was judged to be appropriate for the structures represented by the design space used in this study.

Median collapse capacities were inferred from the code minimum base shear strength for each archetype. Using the code minimum base shear strength, the effective value of the design spectral acceleration at the fundamental period, S_{aD}, at which the structure satisfies all applicable seismic design criteria of ASCE/SEI 7-10, was determined using FEMA P-58, Volume 1, Equation 6-2:

$$S_{aD} = \frac{V}{W} R$$

where V is the code-minimum base shear strength, W is the seismic weight, and R is the response modification coefficient for the structure, as defined in ASCE/SEI 7-10. The inferred median collapse capacity, $\hat{S}_a\left(T_1\right)$, at the fundamental period, T_1, was determined using a modified version of FEMA P-58, Volume 1, Equation 6-3:

$$\hat{S}_a\left(T_1\right) = 2(OF)S_{aD}$$

where OF is the design space overstrength factor, which is based on the system and the point of interest in the design space. For the purpose of calculating collapse fragility, the design space overstrength factor, OF, at all points in the design space was taken as upper bound multiple of the code minimum base shear strength (from Table 3-3), and was never taken less than 2.0 at any point in the design space.

Because archetypes have identical structural properties in each orthogonal direction, the average fundamental period, $\overline{T}_1$, is equal to T_1, and $\hat{S}_a\left(\overline{T}_1\right) = S_a\left(T_1\right)$ for all archetypes.

3.7.1 Casualty Assumptions

For all collapse fragilities, a single partial collapse mode was considered, assuming 30 percent of the floor area collapses. Within the collapsed area, 30 percent of the building population was assumed to be fatalities, and 70 percent was assumed to sustain serious injuries. As regular, well-configured structures, a dispersion, β, of 0.6 was assumed across all archetypes.

3.8 Summary of Representative Archetypical Properties

Structural properties at each point in the design space are unique and are different for each of the 1,755 combinations of system, risk category, hazard level, building height, and design space point. Because representative designs are combinations of lateral strength and stiffness judged to be most typical for each seismic force-resisting system, properties of representative designs are reported to provide a sense of the structural properties for each system, and the variation between systems.

Representative designs are not necessarily one of the 13 points in the design space, and are generally taken as the average of three or four points. Tables 3-7 to 3-11 summarize the range of key structural parameters calculated at representative design points for SDC D archetypes in each system.

Table 3-7 Range of Structural Properties for Representative Design Points, Steel SMRF Archetypes, SDC D

Height	Risk Category	Periods			Drift Ratios		Strengths	
		Bare-Frame Period, $T_{1,BF}$	Effective Period, $T_{1,EFF}$	Upper Limit Period, T_{max}	Design Story Drift Ratio	Yield Drift Ratio (%)	Minimum Base Shear Coefficient, C_s	Inferred Collapse Capacity, g
Low-Rise	II	1.25 - 1.45	1.06 - 1.23	0.73	0.021 - 0.025	1.0	0.10	3.7 - 6.1
	IV	0.83 - 0.90	0.70 - 0.76	0.73	0.014 - 0.015	1.0	0.15 - 0.16	5.8 - 9.6
Mid-Rise	II	1.52 - 1.72	1.29 - 1.46	1.11	0.018 - 0.02	1.0	0.07	2.4 - 4.1
	IV	0.79 - 0.90	0.67 - 0.77	1.11	0.009 - 0.01	1.0	0.15 - 0.17	6.0 - 10.0
High-Rise	II	2.46 - 2.63	2.09 - 2.24	2.23	0.018 - 0.02	1.0	0.03 - 0.04	1.3 - 2.2
	IV	-	-	-	-	-	-	-

Table 3-8 Range of Structural Properties for Representative Design Points, RC SMRF Archetypes, SDC D

Height	Risk Category	Periods			Drift Ratios		Strengths	
		Bare-Frame Period, $T_{1,BF}$	Effective Period, $T_{1,EFF}$	Upper Limit Period, T_{max}	Design Story Drift Ratio	Yield Drift Ratio (%)	Minimum Base Shear Coefficient, C_s	Inferred Collapse Capacity, g
Low-Rise	II	1.25 - 1.45	0.69 - 0.80	0.61	0.021 - 0.025	0.55	0.12	4.0 - 5.2
	IV	0.83 - 0.90	0.45 - 0.49	0.61	0.014 - 0.015	0.55	0.19	6.0 - 7.9
Mid-Rise	II	1.52 - 1.72	0.83 - 0.94	0.96	0.018 - 0.02	0.55	0.09 - 0.09	2.9 - 3.8
	IV	0.79 - 0.90	0.44 - 0.50	0.96	0.009 - 0.01	0.55	0.19	6.0 - 7.9
High-Rise	II	2.46 - 2.63	1.35 - 1.45	2.11	0.018 - 0.02	0.55	0.05 - 0.06	1.8 - 2.3
	IV	-	-	-	-	-	-	-

Table 3-9 Range of Structural Properties for Representative Design Points, Steel BRBF Archetypes, SDC D

Height	Risk Category	Periods			Drift Ratios		Strengths	
		Bare-Frame Period, $T_{1,BF}$	Effective Period, $T_{1,EFF}$	Upper Limit Period, T_{max}	Design Story Drift Ratio	Yield Drift Ratio (%)	Minimum Base Shear Coefficient, C_s	Inferred Collapse Capacity, g
Low-Rise	II	0.62 - 0.77	0.53 - 0.65	0.48	0.01 - 0.0125	0.3	0.13	4.0 - 5.3
	IV	0.62 - 0.77	0.53 - 0.65	0.48	0.01 - 0.0125	0.3	0.19	6.0 - 7.9
Mid-Rise	II	0.98 -1.21	0.84 - 1.03	0.96	0.01 - 0.0125	0.3	0.08 - 0.09	2.5 - 3.3
	IV	0.75 - 0.87	0.64 - 0.74	0.96	0.008 - 0.009	0.3	0.15 - 0.18	4.9 - 6.4
High-Rise	II	2.15 - 2.43	1.83 - 2.07	1.85	0.013 - 0.016	0.3	0.04	1.3 - 1.7
	IV	-	-	-	-	-	-	-

Table 3-10 Range of Structural Properties for Representative Design Points, Steel SCBF Archetypes, SDC D

Height	Risk Category	Periods			Drift Ratios		Strengths	
		Bare-Frame Period, $T_{1,BF}$	Effective Period, $T_{1,EFF}$	Upper Limit Period, T_{max}	Design Story Drift Ratio	Yield Drift Ratio (%)	Minimum Base Shear Coefficient, C_s	Inferred Collapse Capacity, g
Low-Rise	II	0.37 - 0.53	0.32 - 0.45	0.32	0.005 - 0.01	0.35	0.17	4.0
	IV	0.35 - 0.48	0.30 - 0.41	0.32	0.004 - 0.008	0.35	0.25	6.0
Mid-Rise	II	0.47 - 0.73	0.40 - 0.62	0.64	0.005 - 0.01	0.35	0.16 - 0.17	3.9 - 4.0
	IV	0.44 - 0.60	0.38 - 0.51	0.64	0.004 - 0.008	0.35	0.25	6.0
High-Rise	II	1.21 - 2.05	1.03 - 1.75	1.24	0.009 - 0.016	0.35	0.08 -0.10	1.94 - 2.34
	IV	-	-	-	-	-	-	-

Table 3-11 Range of Structural Properties for Representative Design Points, Special RCSW Archetypes, SDC D

Height	Risk Category	Periods			Drift Ratios		Strengths	
		Bare-Frame Period, $T_{1,BF}$	Effective Period, $T_{1,EFF}$	Upper Limit Period, T_{max}	Design Story Drift Ratio	Yield Drift Ratio (%)	Minimum Base Shear Coefficient, C_s	Inferred Collapse Capacity, g
Low-Rise	II	0.21 - 0.33	0.19 - 0.30	0.32	0.003 - 0.006	0.5	0.20	4.5 - 7.5
	IV	0.21 - 0.33	0.19 - 0.30	0.32	0.003 - 0.006	0.5	0.30	6.8 - 11.3
Mid-Rise	II	0.29 - 0.47	0.26 - 0.42	0.64	0.003 - 0.006	0.26	0.20	4.5 - 7.5
	IV	0.29 - 0.47	0.26 - 0.42	0.64	0.003 - 0.006	0.26	0.30	6.8 - 11.3
High-Rise	II	1.02 - 1.41	0.92 - 1.27	1.24	0.009 - 0.013	0.63	0.10 - 0.13	2.9 - 4.9
	IV	-	-	-	-	-	-	-

Properties for representative low SDC D and SDC E/F archetypes are provided in Appendix A. As noted in Appendix A, archetypes at all three hazard levels conform to design and detailing requirements for Seismic Design Category D buildings, but designs vary between hazard levels.

In the simplified design approach, design story drift ratios are determined by the point of interest in the design space, and the resulting stiffness, and base shear are back-calculated using code-based strength and period equations. Although design story drift ratios are the same at each hazard level, the designs vary between hazard levels due to differences in design spectra and the resulting spectral response acceleration parameters S_{DS} and S_{D1}. Because the required design forces change with hazard, the resulting periods (i.e., stiffnesses) must change accordingly to match the specified drift ratios at different force levels. As a result, properties for Low SDC D archetypes are weaker and more flexible than SDC D archetypes, and properties for SDC E/F archetypes are stronger and stiffer than all other archetypes.

3.9 Estimation of Structural Demands

The simplified analysis procedure in FEMA P-58, Volume 1 was used to calculate pseudo lateral forces and median estimates of drift, acceleration, and velocity demands for each archetype. Structural information needed to implement the simplified analysis procedure includes the effective fundamental period, first mode shape, total seismic weight, first mode effective weight, and expected yield strength of the archetype.

To assess performance at different levels of earthquake shaking, structural demands were calculated at five levels of shaking intensity, expressed as a percentage of MCE ground shaking intensity. Intensity levels used to assess performance are summarized in Table 3-12. Intensity 3 is intended to represent the ASCE/SEI 7-10 Design Earthquake level, and intensity 5 is the MCE level.

Table 3-12 Intensity Levels Used to Calculate Demands and Assess Performance, as a Percentage of MCE

Intensity Level	1	2	3	4	5
IntMCE	20%	40%	67%	80%	100%

Median estimates of story drift ratio, Δ_i^*, floor acceleration, a_i^*, and floor velocity, v_i^*, were computed using the simplified analysis procedure as follows:

- The pseudo lateral force, V, was calculated and distributed over the height of the archetype.

- Floor displacements and uncorrected story drifts were computed. Story drifts were divided by story height to obtain story drift ratios.
- Story drift ratios were corrected to account for inelastic behavior and higher mode effects using simplified analysis correction factors for drift from FEMA P-58, Volume 1.
- Peak floor acceleration was estimated at each floor from peak ground acceleration using simplified analysis correction factors for acceleration from FEMA P-58, Volume 1.
- Peak floor velocity was estimated at each floor from peak ground velocity using simplified analysis correction factors for velocity from FEMA P-58, Volume 1.

In this study, the simplified analysis procedure was expanded to include improved drift, acceleration, and velocity correction factors for special concentrically braced frame and buckling-restrained braced frame systems developed in Saldana and Terzic, 2018 (FEMA P-58/BD-3.7.21 Report). The floor level, story level, and floor height designation numbering system used in the simplified analysis procedure calculations is shown in Figure 3-1.

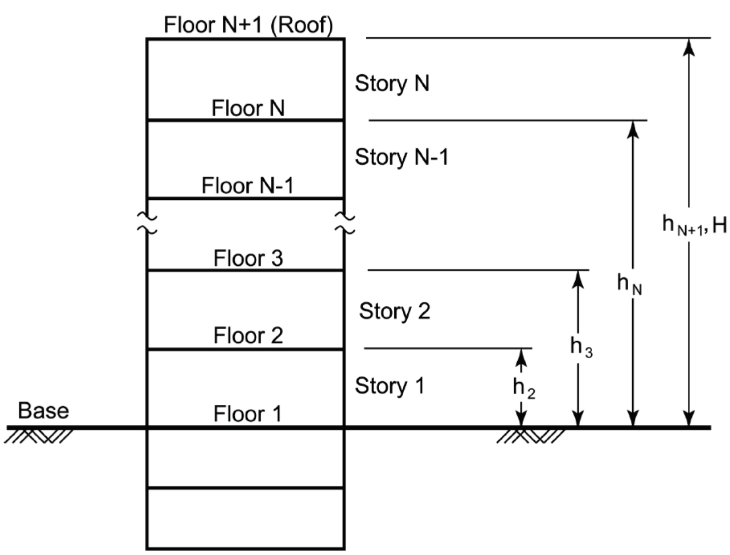


Figure 3-1 Definition of floor levels, story numbers, and floor heights used in the simplified analysis procedure (FEMA P-58, Volume 1).

3.9.1 Pseudo-Lateral Force

The simplified analysis procedure of FEMA P-58, Volume 1 uses a pseudo lateral force, V, to compute story drift ratios, velocities, and accelerations. Pseudo lateral force computations are similar to those found in ASCE/SEI 41-17, and are different from those obtained using ASCE/SEI 7-10 equivalent lateral force procedures. The pseudo lateral force was computed using FEMA P-58, Volume1, Equation 5-3:

$$V = C_1 C_2 S_a(T_1) W_1$$

where C_1 is an adjustment factor for inelastic displacements; C_2 is an adjustment factor for cyclic degradation; $S_a(T_1)$ is the 5 percent damped spectral acceleration at the effective fundamental period of the building (as modified for period stiffening effects) at the intensity level of interest; and W_1 is the first modal effective weight, taken as not less than 80 percent of the total weight, W.

The adjustment factors C_1 and C_2 were computed in accordance with FEMA P-58, Volume 1:

$$C_1 = 1 + \frac{S-1}{0.04a} \qquad \text{for } T_1 \le 0.2 \text{ sec}$$

$$C_1 = 1 + \frac{S-1}{aT_1^2} \qquad \text{for } 0.2 < T_1 \le 1 \text{ sec}$$

$$C_1 = 1 \qquad \text{for } T_1 > 1 \text{ sec}$$

where a is a function of the soil site class (for site class D, a = 60), and S is the strength ratio given by FEMA P-58, Volume 1, Equation 5-6:

$$S = \frac{S_a(T_1)W}{V_{y1}}$$

where V_{y1} is yield strength of the building in first mode response estimated in Section 3.5, and W is the total seismic weight. If the value of the strength ratio, S, is less or equal to 1.0, then C_1 is taken as 1.0.

When the value of S is less or equal to 1.0, C_2 is also taken as 1.0. When S is greater than 1.0, C_2 is computed as:

$$C_2 = 1 + \frac{(S-1)^2}{32} \qquad \text{for } T_1 \le 0.2 \text{ sec}$$

$$C_2 = 1 + \frac{(S-1)^2}{800T_1^2} \qquad \text{for } 0.2 < T_1 \le 1 \text{ sec}$$

$$C_2 = 1 \qquad \text{for } T_1 > 0.7 \text{ sec}$$

The first mode effective weight, W_1, was calculated from FEMA P-58, Volume 1, Equation 5-4:

$$W_1 = \frac{\left(\sum_{j=2}^{N+1} w_j \phi_{j1}\right)^2}{\sum_{j=2}^{N+1} w_j \phi_{j1}^2}$$

where w_j is the lumped weight at floor level j, and N is the number of floors in the building above the base.

3.9.2 Floor Displacements and Corrected Story Drift Ratios

The displacement profile of the building at level j that corresponds to the lateral force V was taken as:

$$D_j = C_1 C_2 \Gamma_1 \phi_{j1} (S_a(T_1)/\omega^2) g$$

where ϕ_{j1}, is the jth ordinate of the first mode shape (determined using the simplified structural analysis procedures in Section 3.3), Γ_1 is the modal participation factor, ω is the first circular frequency of vibration, and g is the gravitational constant.

For uniform weight over the building height, the modal participation factor, Γ_1, is:

$$\Gamma_1 = \frac{W_1}{L_1^h} = \frac{W_1}{\sum_{j=2}^{N+1} \frac{W}{N} \phi_{j1}} \frac{\sum_{j=2}^{N+1} \phi_{j1}}{\sum_{j=2}^{N+1} \phi_{j1}^2}$$

Because W_1 may not be taken as less than 80 percent of the effective seismic weight, the modal participation factor Γ_1 cannot be less than:

$$\Gamma_{1,\min} = \frac{0.8W}{L_1^h} = \frac{0.8N}{\sum_{j=2}^{N+1} \phi_{j1}}$$

The uncorrected story drift ratio Δ_i at story i is:

$$\Delta_i = (D_{j+1} - D_j)/h_i$$

where D_j and D_{j+1} are lateral displacements of the floor levels immediately above and below the story and h_i is the story height of story i.

Story drift ratios were corrected to account for inelastic behavior and higher mode effects. Estimates of median story drift ratio, Δ_i^*, for each story i, were calculated using FEMA P-58, Volume 1, Equation 5-10:

$$\Delta_i^* = H_{\Delta i}\left(S, T_1, h_i, H\right) \times \Delta_i$$

where $H_{\Delta i}\left(S,T_1,h_i,H\right)$ is the drift correction factor for story i computed from FEMA P-58, Volume 1, Equation 5-11:

$$\ln\left(H_{\Delta i}\right)=a_0+a_1T_1+a_2S+a_3\frac{h_{i+1}}{H}+a_4\left(\frac{h_{i+1}}{H}\right)^2+a_5\left(\frac{h_{i+1}}{H}\right)^3$$

$$\text{for } S\geq 1,\ i=1 \text{ to } N$$

The values of the coefficients a_0 through a_5 were obtained from FEMA P-58, Volume 1, Table 3-7 and Table 3-8, and Saldana and Terzic, 2018 (FEMA P-58/BD-3.7.21 Report); S is the strength ratio; T_1 is the effective fundamental period including period stiffening effects; and H is the total building height above the base, as defined in Figure 3-1. If the response is elastic, $H_{\Delta i} = 1$.

3.9.3 Peak Floor Accelerations

At the base of the building, peak floor acceleration is equal to the peak ground acceleration. At other floor levels, i, the estimated median peak floor acceleration, a_i^*, relative to a fixed point in space, was derived from the peak ground acceleration using FEMA P-58, Volume 1, Equation 5-12:

$$a_i^*=H_{ai}\left(S,T,h_i,H\right)\times PGA$$

where PGA is the peak ground acceleration; and $H_{ai}\left(S,T,h_i,H\right)$ is the acceleration correction factor for floor i computed from FEMA P-58, Volume 1, Equation 5-13:

$$\ln\left(H_{ai}\right)=a_0+a_1T_1+a_2S+a_3\frac{h_i}{H}+a_4\left(\frac{h_i}{H}\right)^2+a_5\left(\frac{h_i}{H}\right)^3$$

$$\text{for } S\geq 1,\ i=2 \text{ to } N+1$$

The values of the coefficients a_0 through a_5 were obtained from FEMA P-58, Volume 1, Table 3-7 and Table 3-8, and Saldana and Terzic, 2018 (FEMA P-58/BD-3.7.21 Report). If the response is elastic, S was taken as 1.0.

3.9.4 Peak Floor Velocities

At the base of the building, peak floor velocity is equal to the peak ground velocity, PGV, estimated by dividing the spectral velocity at a period of one second, S_v(1.0 s), by a factor of 1.65 (Newmark and Hall, 1982; Huang and Whittaker, 2012).

Spectral velocity at a period of 1 second can be derived from spectral acceleration at a period of one second using FEMA P-58, Volume 1, Equation 5-14:

$$S_v\left(1.0\text{ s}\right) = \frac{S_a\left(1.0\text{ s}\right)}{2\pi} g$$

where S_a(1.0 s) is the spectral acceleration at 1 second period. Peak ground velocity can then be approximated using FEMA P-58, Volume 1, Equation 5-15:

$$PGV = \frac{S_v\left(1.0\text{ s}\right)}{1.65}$$

At other floor levels, i, the estimated median peak floor velocity, v_i^*, relative to a fixed point in space, was computed from the peak ground velocity and reference floor velocity, v_{si}, using FEMA P-58, Volume 1, Equation 5-16:

$$v_i^* = H_{vi}\left(S, T, h_i, H\right) \times v_{si}$$

where $H_{vi}\left(S, T, h_i, H\right)$ is computed from FEMA P-58, Volume 1, Equation 5-17:

$$\ln\left(H_{vi}\right) = a_0 + a_1 T_1 + a_2 S + a_3 \frac{h_i}{H} + a_4 \left(\frac{h_i}{H}\right)^2 + a_5 \left(\frac{h_i}{h}\right)^3$$

$$\text{for } \; S \geq 1, \; i = 2 \text{ to } N + 1$$

The values of the coefficients a_0 through a_5 were obtained from FEMA P-58, Volume 1, Table 3-7 and Table 3-8, and Saldana and Terzic, 2018 (FEMA P-58/BD-3.7.21 Report). The reference floor velocity, v_{si}, was determined from FEMA P-58, Volume 1, Equation 5-18:

$$v_{si} = PGV + 0.3 \frac{T_1}{2\pi} \left(\frac{V_{y1}}{W_1 / g} \Gamma_1\right) \left(\frac{\delta_i}{\delta_r}\right)$$

where δ_i is the uncorrected displacement of floor i; δ_r is the uncorrected roof displacement with respect to the base, and all other terms are as previously defined.

3.9.5 Residual Drift

Residual drift is an uncertain quantity that is difficult to predict analytically, because values are highly sensitive to component modeling assumptions and ground motion characteristics. The residual drift ratio, Δ_r, was estimated for each archetype using the default residual drift model in FEMA P-58, Volume 1, Equation 5-25, in which residual drift is predicted as a function of the peak transient drift and yield drift:

$$\Delta_r = 0 \quad \text{for} \quad \Delta \le \Delta_y$$
$$\Delta_r = 0.3(\Delta - \Delta_y) \quad \text{for} \quad \Delta_y < \Delta < 4\Delta_y$$
$$\Delta_r = (\Delta - 3\Delta_y) \quad \text{for} \quad \Delta \ge 4\Delta_y$$

where Δ is the median story drift ratio calculated by simplified analysis (Section 3.9.2), and Δ_y is the median story drift ratio calculated at yield (Section 3.6).

3.10 Summary of Structural Demands

Structural demands vary at each level in each of the 1,755 archetypes, and are different for each of the five intensity levels between 20% and 100% MCE. Because it is not possible to present the entire set of demand vectors for each archetype, values for representative designs are reported to provide a sense of the structural demands for each system, and the variation between systems. Tables 3-13 to 3-17 summarize the range of median drifts, accelerations, and velocities for representative design points for each system.

Table 3-13 Range of Median Structural Demands for Representative Design Points, Steel SMRF Archetypes, SDC D, Design Earthquake Level

Height	Risk Category	Story Drift Ratio, %	Residual Drift Ratio, %	Peak Floor Acceleration, g	Peak Floor Velocity, in/sec
Low-Rise	II	1.49 - 2.68	0.15 - 0.50	0.47 - 0.52	22.3 - 34.1
	IV	1.03 - 1.73	0.01 - 0.22	0.52 - 0.57	22.8 - 35.4
Mid-Rise	II	1.09 - 1.85	0.03 - 0.26	0.42 - 0.48	21.5 - 32.7
	IV	0.60 - 1.03	0.00 - 0.01	0.52 - 0.58	22.5 - 36.7
High-Rise	II	0.36 - 1.34	0.00 - 0.11	0.30 - 0.41	21.0 - 33.0
	IV	-	-	-	-

Table 3-14 Range of Median Structural Demands for Representative Design Points, RC SMRF Archetypes, SDC D, Design Earthquake Level

Height	Risk Category	Story Drift Ratio, %	Residual Drift Ratio, %	Peak Floor Acceleration, g	Peak Floor Velocity, in/sec
Low-Rise	II	1.04 - 1.83	0.15 - 0.38	0.46 - 0.52	22.7 - 30.9
	IV	0.54 - 1.00	0.00 - 0.14	0.53 - 0.58	22.7 - 30.7
Mid-Rise	II	0.75 - 1.26	0.06 - 0.21	0.43 - 0.49	22.8 - 30.7
	IV	0.31 - 0.60	0.00 - 0.01	0.53 - 0.59	22.7 - 31.2
High-Rise	II	0.23 - 0.84	0.00 - 0.09	0.35 - 0.56	22.7 - 32.4
	IV	-	-	-	-

Table 3-15 Range of Median Structural Demands for Representative Design Points, Steel BRBF Archetypes, SDC D, Design Earthquake Level

Height	Risk Category	Story Drift Ratio, %	Residual Drift Ratio, %	Peak Floor Acceleration, g	Peak Floor Velocity, in/sec
Low-Rise	II	1.22 - 1.88	0.32 - 0.98	0.69 - 0.88	35.8 - 63.9
	IV	1.20 - 1.91	0.27 - 1.01	0.73 - 0.93	40.6 - 74.4
Mid-Rise	II	0.67 - 1.48	0.11 - 0.58	0.61 - 0.81	28.3 - 66.9
	IV	0.53 - 1.10	0.07 - 0.24	0.69 - 0.90	30.7 - 76.6
High-Rise	II	0.39 - 1.49	0.03 - 0.59	0.52 - 0.70	33.8 - 91.9
	IV	-	-	-	-

Table 3-16 Range of Median Structural Demands for Representative Design Points, Steel SCBF Archetypes, SDC D, Design Earthquake Level

Height	Risk Category	Story Drift Ratio, %	Residual Drift Ratio, %	Peak Floor Acceleration, g	Peak Floor Velocity, in/sec
Low-Rise	II	0.51 - 1.13	0.05 - 0.23	0.99 - 1.48	19.1 - 21.4
	IV	0.39 - 0.88	0.01 - 0.16	1.06 - 1.56	21.7 - 24.0
Mid-Rise	II	0.25 - 0.88	0.00 - 0.16	0.84 - 1.42	20.7 - 24.9
	IV	0.21 - 0.62	0.00 - 0.08	0.93 - 1.50	23.3 - 27.8
High-Rise	II	0.17 - 1.43	0.00 - 0.38	0.60 - 0.93	35.0 - 125.5
	IV	-	-	-	-

Table 3-17 Range of Median Structural Demands for Representative Design Points, Special RCSW Archetypes, SDC D, Design Earthquake Level

Height	Risk Category	Story Drift Ratio, %	Residual Drift Ratio, %	Peak Floor Acceleration, g	Peak Floor Velocity, in/sec
Low-Rise	II	0.11 - 0.35	0.00 - 0.00	0.63 - 0.91	21.2 - 26.8
	IV	0.09 - 0.23	0.00 - 0.00	0.37 - 0.93	21.1 - 30.0
Mid-Rise	II	0.08 - 0.35	0.00 - 0.03	0.59 - 0.90	21.5 - 31.8
	IV	0.07 - 0.34	0.00 - 0.02	0.63 - 0.92	21.3 - 38.5
High-Rise	II	0.11 - 0.72	0.00 - 0.03	0.42 - 0.99	22.7 - 46.0
	IV	-	-	-	-

Demands are shown for the SDC D hazard level, at the design earthquake intensity level, and represent the maximum and minimum values over the height of multi-story archetypes. Drift, acceleration, and velocity demands at other hazard levels, and at different intensity levels, are necessarily different, and not shown here.

Chapter 4
Building Performance Models

PACT building performance models consist of project information, building information, population data, component structural and nonstructural fragilities, performance groups, collapse fragilities, structural analysis results (drift, acceleration, and velocity), and residual drift information. This chapter describes how PACT building performance models were populated in this study.

The fragilities provided in the FEMA P-58 fragility database, as updated in the current phase of work, were used for structural, architectural, mechanical, electrical, and plumbing components in each model. Modifications to FEMA P-58 default fragilities, where they occur, are described in this chapter. For healthcare facilities, custom judgement-based fragilities were developed for selected medical components commonly found in acute care hospital facilities.

4.1 Project Information

Data in the project information section includes the project ID and building description, regional and date cost multipliers, and the solver random seed value. Each archetype was assigned the same regional and date cost multipliers, and the same solver random seed value.

PACT default values for the regional cost and date multipliers were not adjusted. The results of the performance evaluation are, therefore, based on repair cost consequence functions for the Northern California region, dated 2011. Because reported repair costs are expressed as a percentage of replacement cost, the assessment results are generally applicable to any timeframe.

The solver random seed value is a whole number used to initiate all sequences of random number generation utilized in the performance assessment. Setting the value of the random seed to zero will cause PACT to randomly seed each generation sequence. If a different solver random seed number is used for multiple runs of a performance model, the results of each performance assessment will be different, even if there are no changes to the input. In this study, a fixed value of 5 was used for all performance assessments so that results of subsequent performance assessment runs would be identical, provided there were no changes to the input.

4.2 Building Information

The building information section includes the number of stories, replacement costs for the core and shell and entire structure, the maximum number of repair workers per square foot, and typical values for floor area and story height. For each floor, the story height and floor area can be adjusted, as well as factors that adjust repair consequences for floor height, floor occupancy, and the presence of hazardous materials. The area per floor was set equal to 14,000 square feet for all archetypes. Story heights were set at 13 feet for all floors. Basements were not included in the performance models.

The replacement cost used for each occupancy and Risk Category is shown in Table 4-1. The replacement time for all archetypes was set equal to 720 days.

Table 4-1 Replacement Cost and Replacement Time by Occupancy and Risk Category

Occupancy	Risk Category	Replacement Cost		Replacement Time (days)
		Core and Shell (per sq. ft.)	Total (per sq. ft.)	
Office	II	$100	$250	720
	IV	$125	$300	720
Healthcare	II	$100	$500	720
	IV	$150	$700	720

The total loss threshold is the ratio of repair cost to replacement cost that triggers the decision on whether a building is a total loss. When the total loss threshold is set to a value less than 1.0, PACT will report that a building is a total loss in any realization that the loss threshold is exceeded, and damage data for individual components will not be available. In this study, the total loss threshold was set equal to 1.0 to avoid truncation of performance data obtained from the assessments. In practice, building owners may elect to replace rather than repair a damaged building when repair costs are more than about 50 percent of the replacement value of the building (i.e., a total loss threshold of 0.5).

Repair time is strongly influenced by the estimated number of workers performing repairs at a given time. The FEMA P-58 methodology uses a “maximum workers per square foot” parameter, which was set equal to the default value of 0.001 workers per square foot, corresponding to one worker per 1,000 square feet of floor area.

Height factors are applied to each floor and reflect increased repair costs associated with repair of damage in the upper levels of taller structures. These factors were set in accordance with suggested values in FEMA P-58, Volume 2, Table 2-1.

A hazardous materials factor can be used to indicate the presence of hazardous materials in the building. In this study, hazardous materials were not assumed to be present in significant quantities, so a default value of 1.0 was used, meaning there is no increase in repair cost due to hazardous materials.

An occupancy factor was applied to reflect the added cost of performing repairs around ongoing building operations and equipment, and the need to provide extra protection around construction activities in an occupied building. PACT does not currently distinguish between occupied and unoccupied repair conditions. In this study, the occupancy factor in PACT was set to a default value of 1.0 (unoccupied), and then assessment results were post-processed to determine if the occupancy factor should be adjusted. For each shaking intensity, the results of every realization were interrogated. If an "Unsafe Placard" consequence was triggered in the realization, then the building was assumed to be evacuated due to the Unsafe Placard, and “unoccupied” factors from FEMA P-58, Volume 2, Table 2-2 were used. Otherwise, “occupied” factors were used in the accumulation of repair consequences.

4.3 Population Model

The equivalent continuous occupancy (ECO) population model was used for all archetypes, and the same population models were assigned to all floors of a given archetype. The ECO population is a time-weighted average population theoretically occupying a building on a continual basis. It represents the number of persons present, on average, throughout the year, considering all times of day and days of the week, and is expressed as the number of occupants per 1,000 square feet. Values for equivalent continuous occupancy for office and healthcare occupancies were calculated based on information provided in Seligson, 2008 (FEMA P-58/BD-3.7.8 Report). The default equivalent continuous occupancy (ECO) for office occupancies is 0.944 persons per 1000 sq. ft., and for healthcare occupancies is 3.238 persons per 1000 sq. ft.

The use of ECO, rather than a more detailed time-dependent occupancy model, was selected to provide a reasonable estimate of mean casualties, but will not accurately capture dispersion in casualties.

4.4 Structural Fragilities

The determination of structural properties (strength, stiffness, period) and demand quantities (drift, acceleration, and velocity) is described in Chapter 3. Structural fragilities used in the building performance models were selected from the updated and revised PACT fragility database (FEMA, 2018c), which includes many options for each type of structural system. The quantity and type of structural components vary by seismic design category, building height, and risk category.

Each fragility group is identified by a unique classification number based on recommendations contained in NISTIR 6389, *UNIFORMAT II Elemental Classification for Building Specifications, Cost Estimating and Cost Analysis* (NIST, 1999). Structural steel and reinforced concrete fragilities were selected from the PACT fragility database that best characterize the types of structural components typically found in each seismic force-resisting system, considering options compliant with strength and detailing requirements in ANSI/AISC 360, *Specification for Structural Steel Buildings* (AISC, 2010b), ANSI/AISC 341-10, *Seismic Provisions for Structural Steel Buildings* (AISC, 2010a), and ACI 318-11, *Building Code Requirements for Structural Concrete and Commentary* (ACI, 2011). Within each system, an effort was made to utilize the same fragility group for all archetypes.

Structural fragility quantities were determined for each seismic design category (SDC), building height, risk category, and seismic force-resisting system, based on design story forces and structural fragility capacity assumptions. Structural systems for each archetype were designed based on extrapolation from analytical studies on preliminary designs. These studies were used to establish strength and stiffness properties for determining the number of bays of lateral bracing, or length of shear wall, needed. Situations where design drift, rather than lateral strength, governed the size of the structural elements were also considered.

Where possible, the quantity of each structural component is the same for all building performance models in a single design space. If needed, component sizes were varied within the same family of fragilities to keep the structural layout the same.

Sample structural fragilities used in representative, mid-rise, SDC D, Risk Category II archetypes are shown in Tables 4-2 through 4-6. Quantities of structural components are also provided in the tables, by direction (Direction 1/Direction 2). Fragilities for Risk Category IV archetypes, and for all archetypes in other Seismic Design Categories (Low SDC D and SDC E/F), are from the same fragility groups, but may differ in the exact fragility selected. Fragility ID numbers and descriptions are taken from the PACT fragility database.

Table 4-2 Sample Structural Fragilities, Mid-Rise, Steel Special Moment Resisting Frames, SDC D, Risk Category II

Floors	ID	Description	Quantity[(1)]
All Floors	B1031.001	Bolted shear tab gravity connections	36/38
Floor 1	B1031.011b	Steel Column Base Plates, Column 150 plf < *W* < 300 plf	8/8
Floors 1, 2, 3, 4, 5	B1035.001	Post-Northridge RBS connection with welded web, beam one side of column only, beam depth $\leq$ W27	4/4
Floors 1, 2, 3, 4, 5	B1035.011	Post-Northridge RBS connection with welded web, beams both sides of column, beam depth $\leq$ W27	4/4

Notes: (1) Quantities are given as Direction 1/Direction 2.

Table 4-3 Sample Structural Fragilities, Mid-Rise, Reinforced Concrete Special Moment-Resisting Frames, SDC D, Risk Category II

Floors	ID	Description	Quantity[(1)]
All Floors	B1049.032	Post-tensioned concrete flat slabs-columns with shear reinforcing $0.4<V_g/V_o<.0.6$	14/14
Floors 1, 2, 3, 4, 5	B1041.002a	ACI 318 SMF, Conc Col & Bm = 24" × 36", Beam one side	4/4
Floors 1, 2, 3, 4, 5	B1041.002b	ACI 318 SMF, Conc Col & Bm = 24" × 36", Beam both sides	4/4

Notes: (1) Quantities are given as Direction 1/Direction 2.

Table 4-4 Sample Structural Fragilities, Mid-Rise, Steel Buckling-Restrained Braced Frames, SDC D, Risk Category II

Floors	ID	Description	Quantity[(1)]
All Floors	B1031.001	Bolted shear tab gravity connections	40/42
Floor 1	B1031.011b	Steel Column Base Plates, Column 150 plf < *W* < 300 plf	8/8
Floors 1, 2, 3, 4	B1033.101b	Steel Buckling Restrained Brace (BRB), Chevron brace, Weight of brace > 41 plf and < 99 plf	4/4
Floor 5	B1033.101a	Steel Buckling Restrained Brace (BRB), Chevron brace, Weight of brace > 41 plf and < 99 plf	4/4

Notes: (1) Quantities are given as Direction 1/Direction 2.

Table 4-5 Sample Structural Fragilities, Mid-Rise, Steel Special Concentrically Braced Frames, SDC D, Risk Category II

Floors	ID	Description	Quantity[(1)]
All Floors	B1031.001	Bolted shear tab gravity connections	36/38
Floor 1	B1031.011b	Steel Column Base Plates, Column 150 plf < W < 300 plf	8/8
Floors 1, 2, 3, 4	B1033.003b	Special Concentric Braced Frame w/ WF braces, balanced design criteria, X brace, brace 41 plf < W < 99 plf	4/4
Floor 5	B1033.001a	Special Concentric Braced Frame w/ WF braces, balanced design criteria, Chevron brace, brace < 40 plf	4/4

Notes: (1) Quantities are given as Direction 1/Direction 2.

Table 4-6 Sample Structural Fragilities, Mid-Rise, Special Reinforced Concrete Shear Walls, SDC D, Risk Category II

Floors	ID	Description	Quantity[(1)]
All Floors	B1049.032	Post-tensioned concrete flat slabs-columns with shear reinforcing $0.4<V_g/V_o<.0.6$	18/18
Floor 1	B1044.102a	Slender Concrete Wall, 18" thick, 12' high, 20' long	8/8

Notes: (1) Quantities are given as Direction 1/Direction 2.

4.5 Nonstructural Fragilities

General types and typical quantities of nonstructural components in each archetype were based on information from the *Normative Quantity Estimation Tool* in FEMA P-58, Volume 3. For a given building height and occupancy, nonstructural normative quantities are uniform across all archetypes, regardless of the seismic force-resisting system.

Nonstructural fragilities used in the building performance models were selected from the updated and revised PACT fragility database (FEMA, 2018c), which includes many options for each type of nonstructural component and system. Resulting nonstructural fragilities for office and healthcare occupancies are summarized in Appendix B.

4.5.1 Calculation of Nonstructural Fragility Median Capacities

Median capacities for nonstructural components provided in the PACT fragility database are based on testing, expert opinion, or must be determined by the user. Where necessary, median capacities were calculated using the code-based limit state procedures in FEMA P-58, Volume 1, Section 3.8.4, and the seismic design provisions of ASCE/SEI 7-10. Seismic design criteria for nonstructural components depend on many factors, including seismic hazard level, risk category, design story drift, and the location over the height the structure. As a result, nonstructural components and systems required multiple fragilities with different lateral capacities to account for different combinations of factors. Calculation of median capacities for displacement-, acceleration-, and velocity-controlled nonstructural components and systems is described in the sections that follow.

4.5.2 Displacement-Controlled Components

In the FEMA P-58 methodology, the demand parameter for displacement-controlled components is story drift. Drift capacities for displacement-controlled components varied based on the seismic force-resisting system and the point of interest within the design space.

Figure 4-1 shows the design space for a typical mid-rise, steel special concentric braced frame, Risk Category II archetype. For this archetype, displacement-controlled component fragilities were proportioned to accommodate five different design story drift levels: the maximum design story drift ratio, 0.0125, at points 2, 4, and 13; 0.01 at points 6 and 8; 0.0075 at points 9, 10, and 11; 0.005 at points 5 and 7; and the minimum design story drift ratio, 0.0025, at points 1, 3, and 12. Displacement-controlled component fragilities in other archetypes were similarly determined.

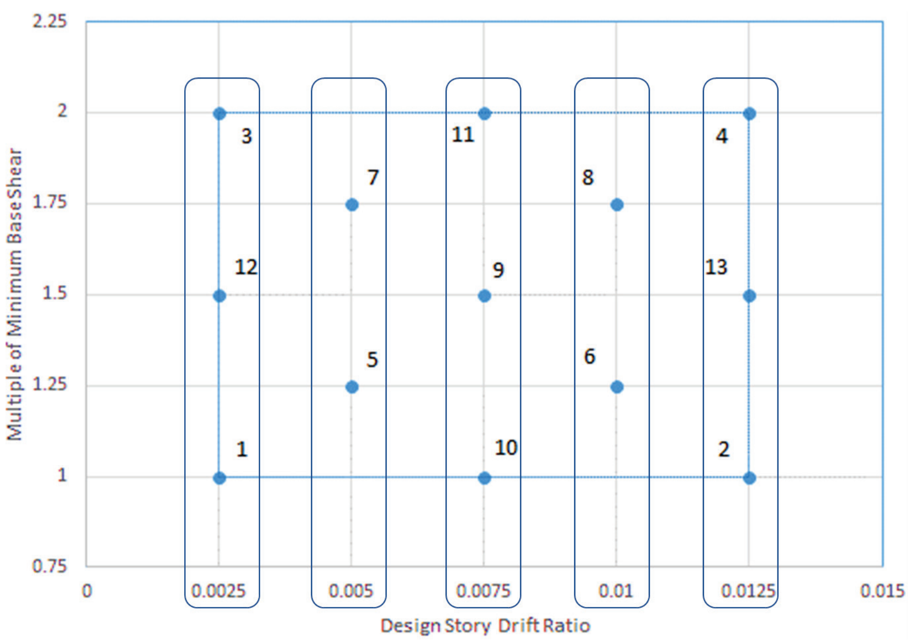


Figure 4-1 Design space for mid-rise, Steel SCBF, Risk Category II archetype, showing drift levels for displacement-controlled nonstructural component fragilities.

In ASCE/SEI 7-10, displacement demands on nonstructural components are expressed as relative seismic displacements, rather than story drift ratios.

The design relative displacement, D_{pI}, was determined using ASCE/SEI 7-10, Equation 13.3-5:

$$D_{pI} = D_p I_e$$

where D_p is the relative seismic displacement that components must be designed to accommodate, and I_e is the importance factor assigned to the structure. The relative seismic displacement demand on a component is the difference in lateral deflections between different points of attachment to the structure. For application to the FEMA P-58 methodology, relative displacement demands were converted to story drifts.

Displacement-controlled nonstructural components include partition walls, curtain wall systems, and exit stairways. Median displacement capacities for partition walls have been established by testing, and are provided in the PACT fragility database. Capacities for curtain wall systems and exit stairs must be determined by calculation for input into the building performance model.

Exterior Curtain Walls. The PACT fragility database provides several different fragilities for curtain wall systems. Median capacities in the database have been determined based on racking tests. Fragilities were selected by equating the median capacity associated with glass fallout to the required relative displacement in ASCE/SEI 7-10, Equation 13.5-1:

$$\Delta_{fallout} \geq 1.25 I_e D_p$$

For curtain wall systems that span from floor to floor, D_p is equal to the drift limit at the point of interest in the design space, Δ_{limit}, and:

$$\Delta_{fallout} \geq 1.25 I_e \Delta_{limit}$$

A total of 23 different curtain wall drift demands were identified across all archetype variants. For each point in the design space a curtain wall fragility was selected from the PACT fragility database such that the median capacity associated with $\Delta_{fallout}$ exceeds the drift demand, $1.25 I_e \Delta_{limit}$. Selected curtain wall fragilities, and the associated drift demands, are shown in Table 4-7.

Table 4-7 includes nine curtain wall fragilities that meet or exceed drift demand requirements. Fragility B2022.032 is a dry-glazed system without any clearance between the glass and the frame. This fragility represents a curtain wall that is suitable for installation in buildings with low story drift demands, and was used where drift demands are less than 0.011. Fragilities for higher drift demands include an allowance for clearance between the glass and the frame. To maintain reasonably close correlation (i.e., to avoid significant over-conservatism) between the design drift demand and the drift

Table 4-7 Selected Glazed Curtain Wall Fragilities and Associated Drift Demands

Fragility ID	Description	Fragility Capacity $\Delta_{fallout}$	Drift Demand $1.25I_e\Delta_{limit}$
B2022.032	Midrise stick-built curtain wall, Config: Monolithic, Lamination: Not laminated, Glass Type: Annealed, Details: 1/4 in. (6 mm) AN monolithic; glass-frame clearance = 0 in. (0 mm); aspect ratio = 6:5 sealant = dry	0.0108	0.004
			0.005
			0.006
			0.007
			0.008
			0.009
			0.0102
			0.0109
B2022.034a	Midrise stick-built curtain wall, Config: Monolithic, Lamination: Not laminated, Glass Type: Annealed, Details: 1/4 in. (6 mm) AN monolithic; Modified median capacities: DS1=0.011, DS2= 0.013	0.013	0.012
			0.013
B2022.034	Midrise stick-built curtain wall, Config: Monolithic, Lamination: Not laminated, Glass Type: Annealed, Details: 1/4 in. (6 mm) AN monolithic; glass-frame clearance = 0.25 in. (6 mm); aspect ratio = 6:5 sealant = dry	0.0164	0.015
			0.016
B2022.035	Midrise stick-built curtain wall, Config: Monolithic, Lamination: Not laminated, Glass Type: Annealed, Details: 1/4 in. (6 mm) AN monolithic; glass-frame clearance = 0.43 in. (11 mm); aspect ratio = 2:1 sealant = dry	0.0212	0.017
			0.018
			0.019
			0.021
B2022.082	Midrise stick-built curtain wall, Config: Symmetric insulating glass units (dual-pane, equal-thickness IGU), Lamination: Not laminated, Glass Type: Annealed, Details: 1 in. (25 mm) AN IGU [1/4 in. (6 mm) inner and outer panes]; glass-frame clearance = 0.25 in. (6 mm); aspect ratio = 6:5 sealant = dry	0.0221	0.022
B2022.002	Curtain Walls – Generic Midrise Stick-Built Curtain wall, Config: Insulating Glass Units (dual pane), Lamination: Unknown, Glass Type: Unknown, Details: Aspect ratio = 6:5, Other details Unknown	0.024	0.024
B2022.036	Midrise stick-built curtain wall, Config: Monolithic, Lamination: Not laminated, Glass Type: Annealed, Details: 1/4 in. (6 mm) AN monolithic; glass-frame clearance = 0.43 in. (11 mm); aspect ratio = 1:2 sealant = dry	0.0257	0.025
B2022.072	Midrise stick-built curtain wall, Config: Symmetric insulating glass units (dual-pane, equal-thickness IGU), Lamination: Laminated, Glass Type: Annealed, Details: 1/4 in. (6 mm) inner AN / 1/4 in. (6 mm) outer AN LAM (0.060 PVB) IGU; glass-frame clearance = 0.43 in. (11 mm); aspect ratio = 6:5 sealant = dry	0.0299	0.026
			0.027
			0.029
B2022.011	Midrise stick-built curtain wall, Config: Asymmetric insulating glass units (dual-pane, unequal-thickness IGU), Lamination: Laminated, Glass Type: Annealed, Details: 1/4 in. (6 mm) inner AN / 1/2 in. (13 mm) outer AN LAM (0.030 PVB) IGU; glass-frame clearance = 0.43 in. (11 mm); aspect ratio = 6:5 sealant = dry	0.0339	0.032

capacity, an additional user-defined fragility, B2022.034a, was created for intermediate values of $\Delta_{fallout}$ and drift demand.

Egress Stairs. In ASCE/SEI 7-10, egress stairs are a designated seismic system, with importance factor I_p = 1.5. FEMA P-58, Volume 2, Section 2.5.5 provides a procedure for estimating the displacement capacity of stairs with seismic joints, which is taken as the design story drift plus the median story drift capacity of a similar stair system without seismic joints. The median capacity for each damage state is, therefore:

$$\theta_i = \Delta_{limit} + \theta_{iN}$$

where θ_i is the median capacity for damage state *i*, and θ_{iN} is the median capacity for damage state *i* for an identical stair without a seismic joint. The dispersion β was taken as 0.50 for all damage states.

4.5.3 Acceleration-Controlled Components

In the FEMA P-58 methodology, the demand parameter for acceleration-controlled components is peak floor acceleration. In ASCE/SEI 7-10, when a nonstructural component is deemed flexible, dynamic interaction between the component and the structure is expected, and design forces are amplified by a_p = 2.5 to account for higher seismic demands.

Use of a_p =2.5 for a component capacity calculation in a FEMA P-58 assessment, however, would make the component anchorage appear more robust than is actually the case. Although a flexible component should be designed for a force that is 2.5 times larger than a rigid component, it is also expected to experience acceleration demands that are 2.5 times larger than what a rigid component would experience. Because peak floor acceleration demands calculated using the FEMA P-58 Simplified Analysis Procedure do not capture dynamic amplification associated with flexible components, the amplification factor, a_p, for capacity calculations was set equal to 1.0, regardless of the tabulated values in ASCE/SEI 7-10. This approach is in general agreement with the recommendations in FEMA P-58, Volume 2, Chapter 7.

The code-based limit state procedures of FEMA P-58, Volume 1, Section 3.8 were used to calculate the median capacity of acceleration controlled nonstructural components. The median capacity is given by FEMA P-58, Volume 1, Equation 3-2:

$$\theta_{brittle} = C_q e^{(2.81\beta)} \phi R_n$$

where C_q is a factor based on sensitivity to construction quality, β is the dispersion based on uncertainty in the ability of design equations to predict actual failure demand, and ϕR_n is the design resistance. For C_q = 0.5 and β = 0.5, the median capacity is:

$$\theta = 2.04\phi R_n$$

The design resistance, ϕR_n, is taken as the ratio of F_p/W_p, where W_p is the component operating weight, and F_p is the horizontal design force calculated using ASCE/SEI 7-10 Section 13.3.1, considering upper and lower limits on the component design force in ASCE/SEI 7-10 Equations 13.3-2 and 13.3-3.

Tables 4-8 through 4-10 provide values of F_p/W_p based on the short-period acceleration parameter, S_{DS}, component response modification factor R_p, and the height of the component in the structure expressed in terms of x/h, where x is the height of the point of attachment of the component, and h is the height of the structure. Values in the tables identified with an asterisk indicate cases in which the ASCE/SEI 7-10 lower limit (Equation 13.3-3) governed.

Table 4-8 Ratio of F_p/W_p for Acceleration-Controlled Components in Low SDC D, Risk Category II Archetypes

	x/h										
R_p	0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0
1.5	0.15*	0.16	0.19	0.21	0.24	0.27	0.29	0.32	0.35	0.37	0.40
2	0.15*	0.15*	0.15*	0.16	0.18	0.20	0.22	0.24	0.26	0.28	0.30
2.5	0.15*	0.15*	0.15*	0.15*	0.15*	0.16	0.18	0.19	0.21	0.22	0.24
3.5	0.15*	0.15*	0.15*	0.15*	0.15*	0.15*	0.15*	0.15*	0.15	0.16	0.17
4.5	0.15*	0.15*	0.15*	0.15*	0.15*	0.15*	0.15*	0.15*	0.15*	0.15*	0.15*
6	0.15*	0.15*	0.15*	0.15*	0.15*	0.15*	0.15*	0.15*	0.15*	0.15*	0.15*

Table 4-9 Ratio of F_p/W_p for Acceleration-Controlled Components in SDC D, Risk Category II Archetypes

	x/h										
R_p	0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0
1.5	0.30*	0.32	0.37	0.43	0.48	0.53	0.49	0.64	0.69	0.75	0.80
2	0.30*	0.30*	0.30*	0.32	0.36	0.40	0.44	0.48	0.52	0.56	0.60
2.5	0.30*	0.30*	0.30*	0.30*	0.30*	0.32	0.35	0.38	0.42	0.45	0.48
3.5	0.30*	0.30*	0.30*	0.30*	0.30*	0.30*	0.30*	0.30*	0.30	0.32	0.34
4.5	0.30*	0.30*	0.30*	0.30*	0.30*	0.30*	0.30*	0.30*	0.30*	0.30*	0.30*
6	0.30*	0.30*	0.30*	0.30*	0.30*	0.30*	0.30*	0.30*	0.30*	0.30*	0.30*

Table 4-10 Ratio of F_p/W_p for Acceleration-Controlled Components in SDC E/F, Risk Category II Archetypes

	x/h										
R_p	0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0
1.5	0.40*	0.43	0.5	0.57	0.64	0.71	0.78	0.85	0.92	0.99	1.06
2	0.40*	0.40*	0.40*	0.43	0.48	0.53	0.59	0.64	0.69	0.74	0.80
2.5	0.40*	0.40*	0.40*	0.40*	0.40*	0.43	0.47	0.51	0.55	0.60	0.64
3.5	0.40*	0.40*	0.40*	0.40*	0.40*	0.40*	0.40*	0.40*	0.40	0.43	0.46
4.5	0.40*	0.40*	0.40*	0.40*	0.40*	0.40*	0.40*	0.40*	0.40*	0.40*	0.40*
6	0.40*	0.40*	0.40*	0.40*	0.40*	0.40*	0.40*	0.40*	0.40*	0.40*	0.40*

Values in the tables are for Risk Category II archetypes (I_e or I_p, equal to 1.0). Values for Risk Category IV archetypes are directly proportional to the change in importance factor.

4.5.4 Velocity-Controlled Components

In the FEMA P-58 methodology, the demand parameter for velocity-controlled components is peak floor velocity. Peak floor velocity demands were calculated using the FEMA P-58 Simplified Analysis Procedure as described in Chapter 3. In this study, velocity-controlled nonstructural components include unanchored medical equipment commonly installed on rollers for easy transport.

Depending on the height-to-width ratio of unanchored equipment, the intensity of the floor velocity, and the nature of the floor surface, components are expected to remain in place, topple, or slide during an earthquake. Fragilities and consequences for velocity-controlled components were calculated based on the procedure for unanchored components in FEMA P-58, Volume 1, using the following judgmentally-determined, mutually exclusive damage states:

- **Damage State 1:**
    - Demand: floor velocity that causes the component to slide 6 inches.
    - Consequences: minor impact, but component remains functional.
- **Damage State 2:**
    - Demand: floor velocity that causes the component to slide 12 inches.
    - Consequences: significant impact, component non-functional and damaged beyond repair.

From FEMA P-58, Volume 1, Equation 3-15, the median peak floor velocity at which a component will slide a distance, δ, is:

$$\hat{V}_{PT} = \frac{\sqrt{2\mu_D g\delta}}{1.37}$$

where μ_D is the dynamic coefficient of friction between the component and its supporting surface, g is the acceleration of gravity, and δ is the critical sliding displacement. Static and dynamic coefficients of friction were taken from FEMA P-58, Volume 2, Chapter 7.

4.5.5 Medical Component Fragilities

Building performance models for healthcare occupancies include fragilities for fixed and mobile medical equipment. Fixed (i.e., anchored) components are acceleration-controlled, and median capacities were determined as described in Section 4.5.3. The component importance factor, I_p, for fixed medical components was set to 1.5 for acute-care hospital archetypes and to 1.0 for outpatient medical building archetypes. Mobile components are velocity-controlled, and median capacities were determined as described in Section 4.5.4. All mobile medical equipment was assumed to have casters or wheels with the locks engaged, resting on floors with a "slick" surface (e.g., poly/tetra/fluoro/ethylene-to-steel surface).

Damage State 1 was assumed to have an 80 percent probability of occurrence, and the component was assumed to be damaged but repairable at a cost of 10 percent of the replacement cost. Damage State 2 was assumed to have a 20 percent probability of occurrence, and the component was assumed to be damaged beyond repair.

Assumed repair and replacement costs were based on list price data for typical medical equipment available at the time of this study. Replacement costs consider only the cost of the component, and do not include ancillary work required to access or reinstall the damaged component. Assumed repair times ranged from 7 to 180 days, depending on the damage state and the cost and complexity of the component. Repair/replacement costs and repair times for medical component fragilities used in this study are judgement-based estimates, and should be considered to be lower bound values. Medical equipment fragilities and consequence data used in this study are provided in Appendix B.

4.5.6 Interior Flooding Fragilities

Building performance models include consideration of the effects of interior flooding. If interior flooding occurs on a floor, it was assumed to impact the entire floor plate, but was not assumed to spread between floors. Flooding fragilities incorporated into the performance models represent office or healthcare facilities located in a dry climate. Interior flooding in a dry climate has a lower likelihood for developing mold subsequent to the flooding event.

Median capacities and dispersions for interior flooding fragilities were controlled by the performance of small diameter threaded steel piping, which is the weakest piping system selected from the PACT fragility database.

4.6 Performance Groups and Representative Nonstructural Fragilities

Performance groups are groups of fragilities that are subjected to the same demands (e.g., story drift, floor acceleration, or velocity), in a particular direction, at a particular floor level. Nonstructural component fragilities in office and healthcare occupancies were based on information from the *Normative Quantity Estimation Tool* in FEMA P-58, Volume 3, and additional assumptions described below.

The types and quantities of nonstructural components are the same for Risk Category II and Risk Category IV archetypes of the same occupancy. The specific fragilities, however, vary based on risk category, seismic hazard level, and location of the component in the structure.

4.6.1 Office Occupancies

Nonstructural fragilities used in commercial offices and emergency operations centers were based on an assumption of 100 percent office occupancy on every floor level, with mechanical equipment located on the roof. The types and quantities of nonstructural component fragilities in representative Risk Category II, mid-rise, office archetypes are provided in Appendix B. Nonstructural fragilities in Risk Category IV emergency operations center archetypes were assumed to be similar, but were selected based on Risk Category IV seismic criteria.

4.6.2 Healthcare Occupancies

Nonstructural fragilities used in healthcare occupancies were based on assumptions for general acute-care hospitals providing surgical, imaging, and laboratory services to patients staying longer than 24 hours, and outpatient medical facilities providing diagnostic imaging and outpatient surgeries to patients staying less than 24 hours. The *Normative Quantity Estimation Tool* was used for typical nonstructural components such as partitions, ceilings, mechanical equipment, and mechanical distribution systems. A medical equipment inventory from a typical acute care hospital formed the basis for medical components assumed in this study.

Department block diagrams, such as the diagram shown in Figure 4-2, were developed for low- and mid-rise healthcare archetypes to determine the location of medical equipment within the building. Although most healthcare facilities providing a full array of medical services will have a larger floor plate than the 14,000 square foot floor area assumed for the archetypes in this study, the floor area for office and healthcare occupancies was held constant to allow comparisons between occupancies. Typical proportions of building area devoted to patient beds, surgical services, and support services, as depicted in the block diagrams, were maintained in low- and mid-rise healthcare archetypes.

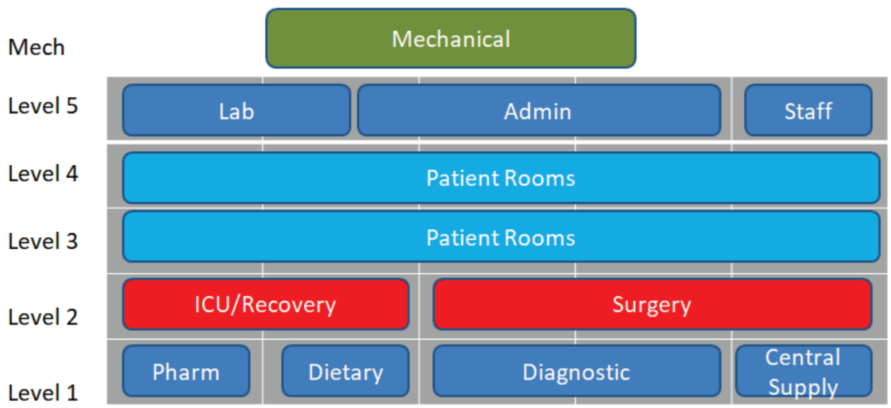


Figure 4-2 Sample department block diagram for mid-rise healthcare archetypes.

The types and quantities of nonstructural component fragilities in representative Risk Category II, healthcare archetypes are provided in Appendix B. In general, the types and quantities of nonstructural components and medical equipment would differ between non-acute care outpatient medical buildings and general acute care hospital buildings, especially for equipment associated with surgical services. However, to investigate the influence of seismic design criteria on performance, nonstructural component fragilities for Risk Category II archetypes (non-acute care outpatient medical buildings) and Risk Category IV archetypes (general acute care hospitals) were assumed to be identical, except for seismic design criteria.

A significant percentage of medical equipment is mobile and not subject to code requirements for seismic bracing and anchorage. Because such components are critical to the operation of a medical facility, and represent a sizable investment, they were included in building performance models for healthcare occupancies. Fragility and consequences functions for medical equipment were developed as described in Section 4.5.5. The types and quantities of medical equipment fragilities used in representative mid-rise, Risk Category II, healthcare archetypes are provided in Appendix B.

Chapter 5
System-Specific Performance of Buildings

This chapter presents system-specific results of FEMA P-58 seismic performance assessments on 1,755 archetypes across five structural systems representative of buildings conforming to the seismic design requirements of ASCE/SEI 7-10 and applicable material design standards. Assessment results are organized to provide information on expected performance given different seismic-force resisting systems, design story drift ratios, lateral strengths, risk categories, hazard levels, building heights, and occupancy types.

The resulting data are voluminous. An interactive tool was developed as a repository of all assessment results and can be used as an interface for viewing results for a specific system and a given set of design assumptions. The *Performance Estimation Tool* (PET) is described in Appendix C and is provided in electronic format in FEMA P-58, Volume 3.

Sample results are presented to illustrate significant findings. To draw generalized conclusions between systems and design requirements, results have been sorted by key parameters, and data have been presented as an average of a spectrum of archetypes representing the entire range, or a selected portion, of the design space.

5.1 Performance Metrics

FEMA P-58 performance metrics include repair costs, repair time, casualties, and probability of incurring an unsafe placard as direct outputs of the *Performance Assessment Calculation Tool* (PACT). In addition, data from PACT realizations were exported and post-processed to derive additional metrics identified as casualty rates and repairability.

Concurrent with this work, the FEMA P-58 methodology was expanded to assess the probability of generating environmental impacts, including embodied energy and carbon. Because environmental metrics were not available at the time these performance assessments were initiated, environmental losses were not considered in assessing the expected performance of code-conforming buildings.

System-specific performance of buildings is reported in terms of five metrics, defined as follows:

- **Repair Cost.** Repair cost is the cost to restore damaged components to their pre-earthquake condition, 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.
- **Repair Time.** Repair time is the number of days required to restore damaged components to their pre-earthquake condition. Repair time is only a portion of the time needed to return 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.
- **Casualty Rate.** Casualties include loss of life or serious injury requiring hospitalization. Casualty rate is the probability of any one occupant in a building becoming a casualty as a result of an earthquake.
- **Probability of Unsafe Placard.** Probability of Unsafe Placard is the probability that a building will be posted unsafe to occupy following an earthquake, based on the occurrence of structural or nonstructural damage that is considered significant enough to trigger an unsafe posting.
- **Repairability.** Repairability 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 FEMA P58 methodology quantifies building performance metrics in probabilistic terms, recognizing uncertainties that can affect building performance. Results for each metric are provided in the form of a probability distribution, and performance metrics at any confidence level can be reported. Median values provide expected performance in the middle of the distribution (i.e., at a 50% confidence level), meaning half of the possible results are lower and half are higher than the reported value. Similarly, 90th percentile values are such that 90% of the possible results are lower and 10% are higher than the reported value, providing a high confidence that the reported value will not be exceeded. In this study, median results are presented.

5.2 Design Space and Representative 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. In general, assessment results are reported as the average over all archetypes comprising the design space.

The parametric variation of strength and stiffness within the design space could include some combinations of lateral strength and stiffness that are not realistic for some systems. Representative designs are combinations of lateral strength and lateral stiffness that are judged to be most typical for each seismic force-resisting system. Where specifically noted, results for seismic force-resisting systems are reported for buildings with the properties of representative designs. Performance results for representative designs are obtained by averaging the results for archetypes at three or four points in the design space. Points contributing to the performance of representative designs for each seismic force-resisting system are identified in Table 5-1.

Table 5-1 Points in the Design Space Contributing to the Performance of Representative Designs for each System

Seismic Force-Resisting System	Points in the Design Space Contributing to Performance of Representative Designs	
	Low-Rise and Mid-Rise	High-Rise
Steel SMRF	6, 8, 13	6, 8, 13
RC SMRF	6, 8, 13	6, 8, 13
Steel BRBF	6, 8, 9	6, 8, 9
Steel SCBF	5, 6, 10	5, 6, 10
Special RCSW	5, 7, 9, 12	5, 7, 9

5.3 Performance Assessment Results by System

Archetypes in each system include variants by occupancy type (office and healthcare), Risk Category (RC II and RC IV), seismic hazard level (Low SDC D, SDC D, and SDC E/F), building height (low-, mid-, and high-rise), and lateral strength and stiffness combinations within the design space. Systems were assessed at five intensity levels: 20% MCE, 40% MCE, 67% MCE (Design), 80% MCE, and 100% MCE. Performance assessment results reported by system have been averaged across all archetypes in the design space and are summarized in the sections that follow.

5.3.1 Steel Special Moment-Resisting Frames

Median results for steel special moment-resisting frame (SMRF) systems, averaged across all Steel SMRF archetype strength and stiffness combinations, heights, and hazard levels, are summarized in Table 5-2.

Overall, losses in Steel SMRF systems increase, and reparability decreases, as the intensity of shaking increases from 20% MCE to 100% MCE. Between Risk Categories, losses in Steel SMRF systems are lower, and repairability of Steel SMRF systems is higher, for Risk Category IV archetypes relative to Risk Category II archetypes, in both office and healthcare occupancies. Within a given Risk Category, losses in Steel SMRF archetypes for healthcare occupancies are higher than office occupancies because of the presence of high-value medical equipment and increased (24-hour) occupancy associated with healthcare occupancies.

Table 5-2 Average Performance of Steel Special Moment-Resisting Frame Systems – Median Results

Performance Measure	Performance at Each Intensity Level				
	20%	40%	Design	80%	MCE
Risk Category II – Office					
Repair Cost	0%	1%	5%	10%	15%
Repair Time	0 days	4 days	14 days	22 days	41 days
Casualty Rate	0%	0%	0.3%	0.6%	1.0%
Probability of Unsafe Placard	0%	0%	8%	16%	27%
Repairability	100%	100%	97%	93%	86%
Risk Category II – Healthcare (Medical Office Building or Laboratory)					
Repair Cost	0%	3%	13%	23%	49%
Repair Time	1 days	12 days	35 days	51 days	82 days
Casualty Rate	0%	0%	0.3%	0.7%	1.1%
Probability of Unsafe Placard	0%	1%	10%	21%	35%
Repairability	100%	99%	92%	85%	75%
Risk Category IV – Office (Emergency Operations Center)					
Repair Cost	0%	1%	3%	5%	8%
Repair Time	0 days	2 days	11 days	17 days	23 days
Casualty Rate	0%	0%	0.1%	0.3%	0.7%
Probability of Unsafe Placard	0%	0%	1%	5%	13%
Repairability	100%	100%	99%	98%	94%
Risk Category IV – Healthcare (Hospital)					
Repair Cost	0%	1%	3%	6%	9%
Repair Time	0 days	3 days	15 days	22 days	30 days
Casualty Rate	0%	0%	0.1%	0.3%	0.7%
Probability of Unsafe Placard	0%	0%	1%	5%	13%
Repairability	100%	100%	99%	98%	94%

Components contributing to losses in Steel SMRF, Risk Category II and IV, office and healthcare archetypes are shown in Table 5-3. Components identified in the table are the most significant contributors accounting for the majority of losses, and are listed in descending order of importance.

The majority of losses in Steel SMRF archetypes are associated with drift-controlled components. Residual drift is a major contributor to losses in Steel SMRF archetypes at shaking intensities of 67% MCE and higher. Components with less significant contributions to loss (and not listed in Table 5-3) include partitions and acceleration-sensitive components such as mechanical, electrical, and plumbing equipment, and elevators.

Table 5-3 Components Contributing to Losses, Steel Special Moment-Resisting Frame Systems

Occupancy and Risk Category	Intensity Level	Components Contributing to Losses
Risk Category II – Office	Design	Exterior Window System, Residual Drift, Steel Moment Connections
	100% MCE	Residual Drift, Exterior Window Systems, Steel Moment Connections
Risk Category IV – Office	Design	Interior Flooding, Exterior Window System
	100% MCE	Exterior Window Systems, Interior Flooding, Steel Moment Connections
Risk Category II – Healthcare	Design	Medical Equipment, Residual Drift, Exterior Window System
	100% MCE	Residual Drift, Medical Equipment, Exterior Window System, Steel Moment Connections
Risk Category IV – Healthcare	Design	Medical Equipment, Interior Flooding, Exterior Window System
	100% MCE	Medical Equipment, Exterior Window System, Interior Flooding

Risk Category IV structures are designed for higher lateral forces and lower story drift ratios than Risk Category II structures. At lower shaking intensities, the reduction in median losses for Risk Category IV Steel SMRF archetypes is attributed mainly to higher design forces used for the design of nonstructural components, and enhanced detailing for ceilings and pipe, duct, and electrical distribution systems. At higher shaking intensities (greater than 67% MCE), Steel SMRF archetypes benefit from more stringent design story drift criteria, with substantially reduced structural damage and unrepairable residual drift.

More stringent design requirements in Risk Category IV reduce, but do not eliminate, damage to nonstructural components in Steel SMRF archetypes. Interior flooding still contributes significantly to losses in Risk Category IV Steel SMRF archetypes because demands increase, but the capacity of the piping system responsible for interior flooding is not influenced by Risk Category. Damage to medical equipment in Risk Category IV Steel SMRF archetypes is reduced, except in the case of mobile equipment because sliding capacity is not influenced by Risk Category.

The influence of lateral strength and design story drift ratio on median repair costs for Steel SMRF archetypes can be seen in Figure 5-1, which superimposes median losses on the design space for Risk Category II and IV office archetypes, subjected to 100% MCE shaking intensity, averaged over all building heights and hazards levels. In the figure, average median repair costs for Steel SMRF archetypes decrease somewhat as the design story drift ratio decreases across the design space. Reductions are more significant under more stringent Risk Category IV drift requirements because Steel SMRF archetypes designed for lower story drift ratios are less likely to trigger unrepairable residual drift at higher shaking intensities. Variations in lateral strength showed little influence on average median repair costs in Steel SMRF archetypes in either Risk Category.

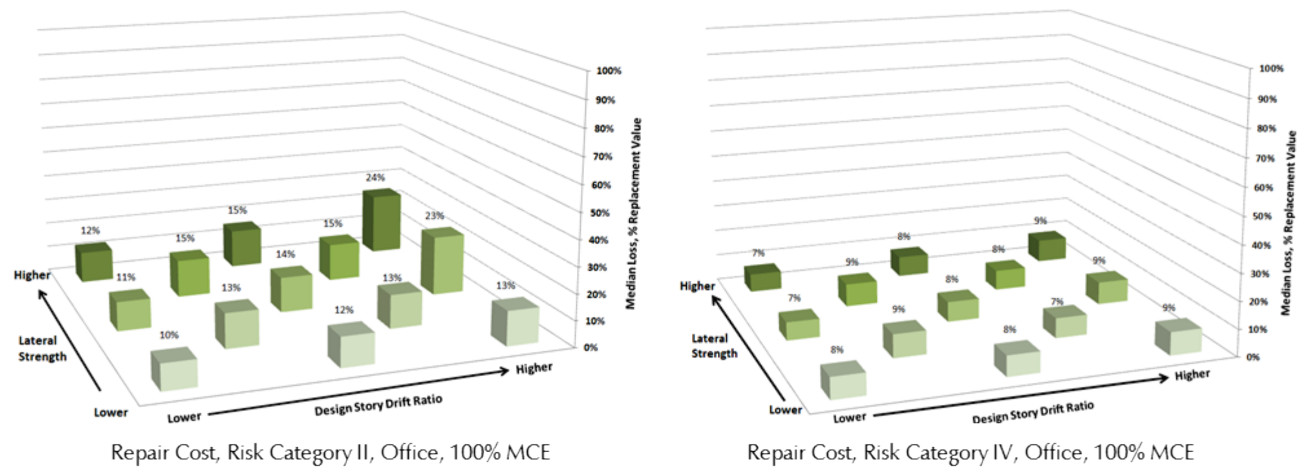
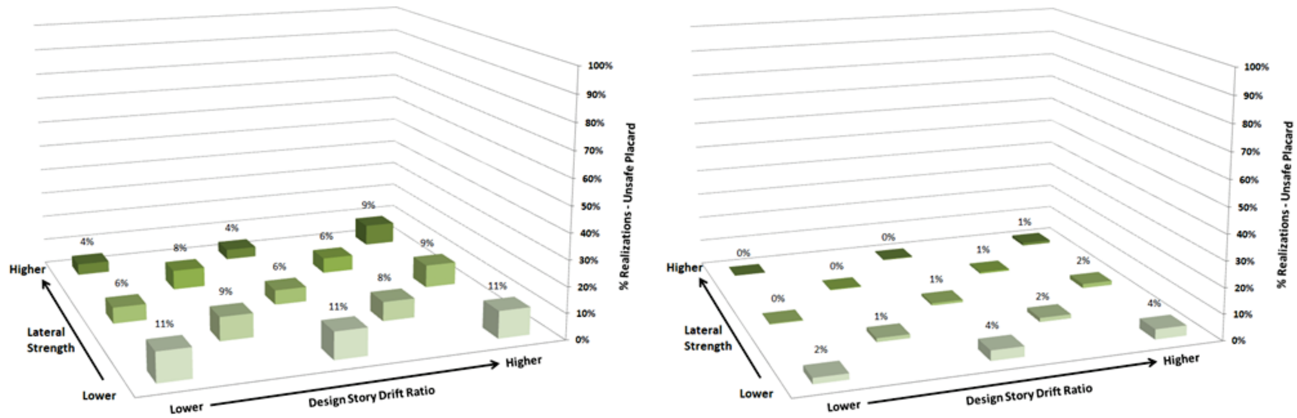


Figure 5-1 Median repair costs for 13 lateral strength/design story drift ratio combinations, Steel SMRF, Risk Category II and IV, office occupancies, 100% MCE.

Figure 5-2 shows the probability of triggering an unsafe placard on the design space for Steel SMRF, Risk Category II and IV office archetypes, subjected to design earthquake (67% MCE) shaking intensity, averaged over all building heights and hazards levels. In the figure, the probability of triggering an unsafe placard is more strongly influenced by lateral strength and design story drift ratio, and overall probabilities of triggering an unsafe placard are more strongly influenced by Risk Category.

Overall, Risk Category IV archetypes showed improved performance over Risk Category II archetypes across all performance metrics, although the level of improvement varied. In the case of median repair times, trends similar to median repair costs were observed. In the case of casualty rate and repairability metrics, variations in lateral strength and design story drift ratio across the design space had much less influence on the performance of Risk Category II or Risk Category IV archetypes in Steel SMRF systems.



Unsafe Placard, Risk Category II, Office, 67% MCE

Unsafe Placard, Risk Category IV, Office, 67% MCE

Figure 5-2 Probability of incurring an unsafe placard for 13 lateral strength/design story drift ratio combinations, Steel SMRF, Risk Category II and IV, office occupancies, 67% MCE.

5.3.2 Reinforced Concrete Special Moment-Resisting Frames

Median results for reinforced concrete special moment-resisting frame (RC SMRF) systems, averaged across all RC SMRF archetype strength and stiffness combinations, heights, and hazard levels, are summarized in Table 5-4. Trends in the results for RC SMRF systems are similar to those reported for Steel SMRF systems.

As observed in Steel SMRF systems, losses in RC SMRF systems increase, and repairability decreases, as the intensity of shaking increases from 20% MCE to 100% MCE. Between Risk Categories, losses in RC SMRF systems are lower, and repairability of RC SMRF systems is higher, for Risk Category IV archetypes relative to Risk Category II archetypes, in both office and healthcare occupancies. Within a given Risk Category, losses in RC SMRF archetypes for healthcare occupancies are higher than office occupancies because of the presence of high-value medical equipment and increased (24-hour) occupancy associated with healthcare occupancies.

Components contributing most significantly to losses in RC SMRF, Risk Category II and IV, office and healthcare archetypes are listed in Table 5-5. Components identified in the table are the most significant contributors accounting for the majority of losses, and are listed in descending order of importance.

Residual drift and damage to concrete connections are major contributors to losses at shaking intensities of 67% MCE and higher in RC SMRF archetypes, although the relative importance varies with sensitivity to drift or acceleration, and was observed to be different among low-rise, mid-rise, and high-rise RC SMRF archetypes. For example, residual drift was the main

Table 5-4 Average Performance of Reinforced Concrete Special Moment-Resisting Frame Systems – Median Results

Performance Measure	Performance at Each Intensity Level				
	20%	40%	Design	80%	MCE
Risk Category II – Office					
Repair Cost	0%	2%	6%	14%	28%
Repair Time	2 days	8 days	20 days	54 days	132
Casualty Rate	0%	0%	0.4%	0.7%	1.2%
Probability of Unsafe Placard	0%	2%	6%	14%	37%
Repairability	100%	100%	99%	91%	80%
Risk Category II – Healthcare (Medical Office Building or Laboratory)					
Repair Cost	0%	3%	12%	22%	38
Repair Time	1 days	11 days	30 days	46 days	70 days
Casualty Rate	0%	0%	0.2%	0.5%	0.9%
Probability of Unsafe Placard	0%	1%	10%	21%	37%
Repairability	100%	99%	92%	83%	75%
Risk Category IV – Office (Emergency Operations Center)					
Repair Cost	0%	0%	2%	4%	7%
Repair Time	0 days	2 days	11 days	17 days	23 days
Casualty Rate	0%	0%	0.0%	0.2%	0.5%
Probability of Unsafe Placard	0%	0%	1%	3%	9%
Repairability	100%	100%	100%	99%	97%
Risk Category IV – Healthcare (Hospital)					
Repair Cost	0%	1%	5%	8%	12%
Repair Time	0 days	7 days	24 days	35 days	47 days
Casualty Rate	0%	0%	0%	0.1%	0.4%
Probability of Unsafe Placard	0%	0%	1%	5%	12%
Repairability	100%	100%	99%	98%	95%

contributor to losses in low-rise archetypes, while damage to concrete beams and flat slab/column connections were the main contributors to losses in mid-rise and high-rise archetypes. This is because low-rise RC SMRF archetypes have larger design story drift ratios than mid- and high-rise archetypes, and RC SMRF archetypes designed for higher story drift ratios are more likely to trigger unrepairable residual drift at higher shaking intensities. Other components with less significant contributions to loss (and not listed in Table 5-5) included partitions and mechanical, electrical, and plumbing equipment.

More stringent Risk Category IV design requirements reduce structural losses in RC SMRF archetypes in shaking intensities greater than 67% MCE, with substantially reduced structural damage and unrepairable residual drift.

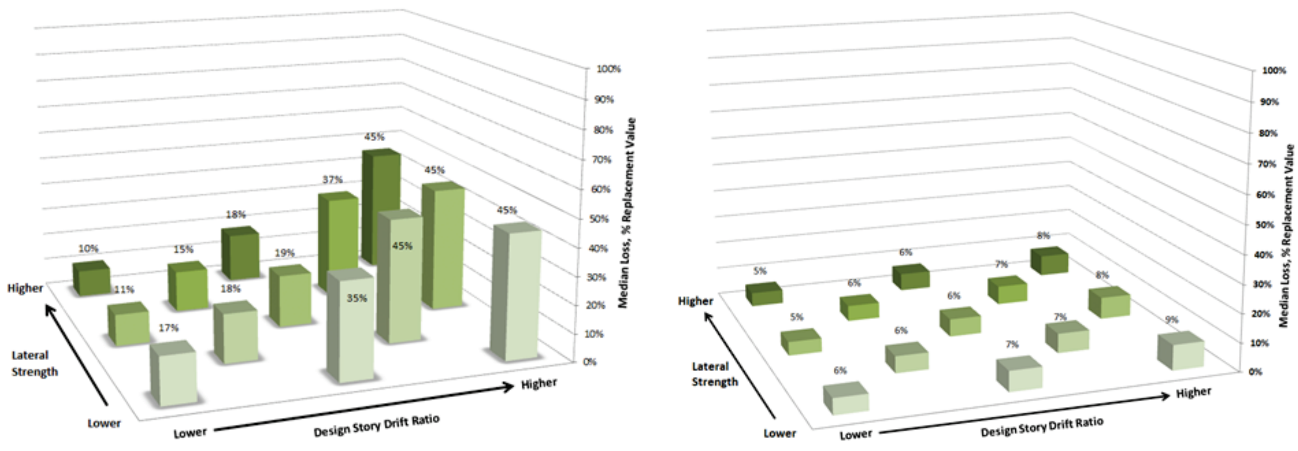
Table 5-5 Components Contributing to Losses, Reinforced Concrete Special Moment-Resisting Frame Systems

Occupancy and Risk Category	Intensity Level	Components Contributing to Losses
Risk Category II – Office	Design	Concrete Beams and Flat Slab/Columns, Residual Drift, Exterior Window System, Interior Flooding
	100% MCE	Residual Drift, Concrete Beams and Flat Slab/Columns, Exterior Window System, Interior Flooding
Risk Category IV – Office	Design	Interior Flooding, Concrete Beams and Flat Slab/Columns, MEP Systems
	100% MCE	Concrete Beams and Flat Slab/Columns, Interior Flooding, Exterior Window System, Residual Drift
Risk Category II – Healthcare	Design	Medical Equipment, Concrete Beams and Flat Slab/Columns, Residual Drift, Exterior Window System, Interior Flooding
	100% MCE	Medical Equipment, Residual Drift, Concrete Beams and Flat Slab/Columns, Exterior Window System, Interior Flooding
Risk Category IV – Healthcare	Design	Medical Equipment, Interior Flooding, Concrete Beams and Flat Slab/Columns
	100% MCE	Medical Equipment, Concrete Beams and Flat Slab/Columns, Interior Flooding, Residual Drift

Risk Category IV design requirements reduce, but do not eliminate, damage to nonstructural components in RC SMRF archetypes. Interior flooding still contributes significantly to losses in Risk Category IV archetypes because demands increase but the capacity of the piping system responsible for interior flooding is not influenced by Risk Category. Damage to medical equipment in Risk Category IV RC SMRF archetypes is reduced, except in the case of mobile equipment because sliding capacity is not influenced by Risk Category.

The influence of lateral strength and design story drift ratio on median repair costs for RC SMRF archetypes can be observed in Figure 5-3, which shows median repair costs on the design space for RC SMRF, Risk Category II, office archetypes, subjected to 100% MCE shaking intensity, averaged over all building heights and hazards levels. In the figure, average median repair costs for RC SMRF archetypes are significantly influenced by both lateral strength and design story drift ratio, and archetypes with higher lateral strengths and smaller design story drift ratios have lower average median repair costs. Reductions are more significant in Risk Category IV, which clearly shows the effect of more stringent drift requirements.

Observed trends are less pronounced at design earthquake (67% MCE) shaking intensities than at MCE shaking intensities. Similar trends are observed for average median repair times across the design space for Risk Category II and Risk Category IV RC SMRF archetypes.

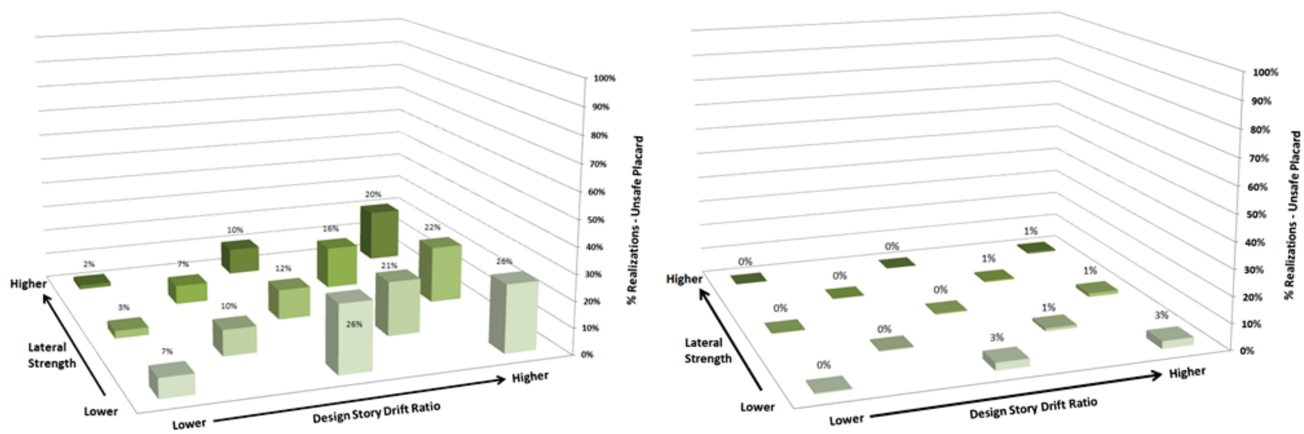


Repair Cost, Risk Category II, Office, 100% MCE

Repair Cost, Risk Category IV, Office, 100% MCE

Figure 5-3 Median repair costs for 13 lateral strength/design story drift ratio combinations, RC SMRF, Risk Category II and IV, office occupancies, 100% MCE.

Figure 5-4 shows the probability of triggering an unsafe placard, averaged over all building heights and hazards levels, on the design space for RC SMRF, Risk Category II and IV, office archetypes, subjected to design earthquake (67% MCE) shaking intensity.



Unsafe Placard, Risk Category II, Office, 67% MCE

Unsafe Placard, Risk Category IV, Office, 67% MCE

Figure 5-4 Probability of incurring an unsafe placard for 13 lateral strength/design story drift ratio combinations, RC SMRF, Risk Category II and IV, office occupancies, 67% MCE.

In the figure, average probabilities of triggering an unsafe placard are influenced by lateral strength and design story drift ratio, and archetypes with higher lateral strengths and smaller design story drift ratios are less likely to trigger an unsafe placard. Overall probabilities of triggering an unsafe placard are strongly influenced by Risk Category.

5.3.3 Steel Buckling-Restrained Braced Frames

Median results for steel buckling-restrained braced frame (BRBF) systems, averaged across Steel BRBF archetype strength and stiffness combinations, heights, and hazard levels, are summarized in Table 5-6.

As observed in other systems, losses in Steel BRBF systems increase, and repairability decreases, as the intensity of shaking increases. The trend in BRBF systems, however, is more pronounced, with comparatively higher losses due to increased sensitivity to drift demands exceeding design drifts, and more frequent occurrence of unrepairable residual drift at higher shaking intensities.

Table 5-6 Average Performance of Steel Buckling-Restrained Braced Frame Systems – Median Results

Performance Measure	Performance at Each Intensity Level				
	20%	40%	Design	80%	MCE
Risk Category II – Office					
Repair Cost	0%	4%	22%	41%	56%
Repair Time	0 days	16 days	121	253	367
Casualty Rate	0%	0.2%	1.1%	1.8%	2.7%
Probability of Unsafe Placard	0%	5%	26%	40%	52%
Repairability	100%	96%	78%	66%	54%
Risk Category II – Healthcare (Medical Office Building or Laboratory)					
Repair Cost	1%	9%	37%	55%	69%
Repair Time	3 days	25 days	149	286	407
Casualty Rate	0%	0.2%	1.0%	1.8%	2.7%
Probability of Unsafe Placard	0%	5%	27%	41%	54%
Repairability	99%	92%	71%	58%	46%
Risk Category IV – Office (Emergency Operations Center)					
Repair Cost	0%	2%	16%	27%	39%
Repair Time	0 days	7 days	92 days	160	244
Casualty Rate	0%	0%	0.6%	1.2%	2.1%
Probability of Unsafe Placard	0%	2%	16%	27%	41%
Repairability	100%	98%	85%	75%	63%
Risk Category IV – Healthcare (Hospital)					
Repair Cost	0%	2%	19%	29%	41%
Repair Time	0 days	9 days	106	167	251
Casualty Rate	0%	0%	0.6%	1.2%	2.1%
Probability of Unsafe Placard	0%	2%	16%	27%	41%
Repairability	100%	98%	85%	75%	63%

Median losses for Steel BRBF systems shown in Table 5-6 reflect a design space that includes code minimum required lateral strengths and, for high-rise archetypes, code maximum permissible drift limits (see Tables 2-5 and 2-6). In the case of low-rise and mid-rise archetypes, engineering practice is expected to result in designs that are stiffer that required, and design drifts were conservatively taken to be less than code maximum drift limits. Even with this level of conservatism, it is likely that the assumed design drift limits for archetypes in this study exceed typical design drifts for Steel BRBF systems used in engineering practice. Losses for Steel BRBF systems would be lower if actual design strengths are more than the minimum required strength, and design drifts are further reduced below permissible drift limits.

Between Risk Categories, losses in Steel BRBF systems are lower, and repairability of Steel BRBF systems is higher, for Risk Category IV archetypes relative to Risk Category II archetypes, in both office and healthcare occupancies. Within a given Risk Category, losses in Steel BRBF archetypes for healthcare occupancies are somewhat higher than office occupancies because of the presence of additional, high-value equipment and increased (24-hour) occupancy associated with healthcare occupancies.

Components contributing most significantly to losses in Steel BRBF, Risk Category II and IV, office and healthcare archetypes are listed in Table 5-7, in decreasing order of importance. Residual drift is a major contributor to losses at shaking intensities of 67% MCE and higher in Steel BRBF archetypes. Other less significant contributors to loss (not listed in Table 5-7) include mechanical, electrical, and plumbing equipment, partitions, and elevators.

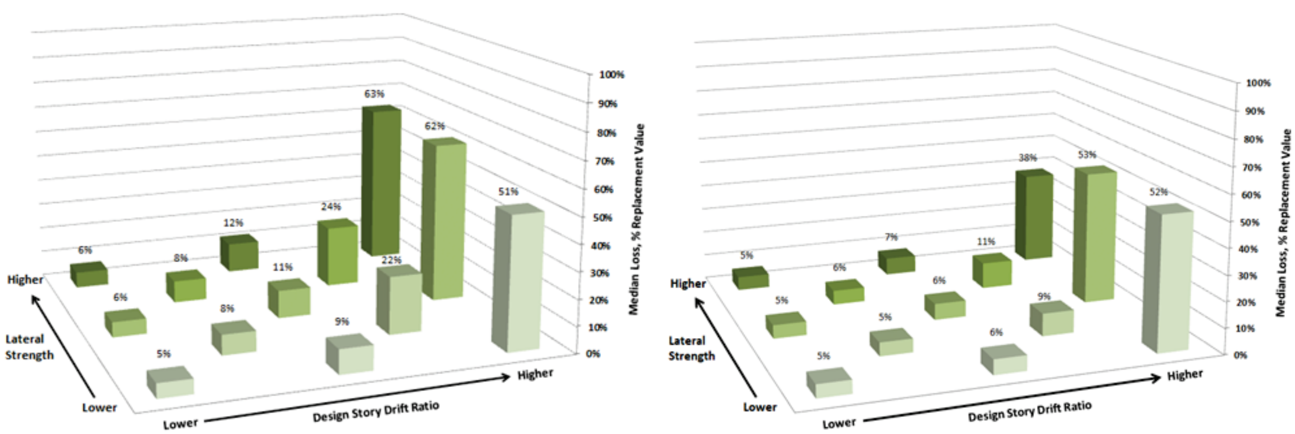
Table 5-7 Components Contributing to Losses, Steel Buckling-Restrained Braced Frame Systems

Occupancy and Risk Category	Intensity Level	Components Contributing to Losses
Risk Category II – Office	Design	Residual Drift, Exterior Window System, Steel Braces, Interior Flooding, Partitions
	100% MCE	Residual Drift, Steel Braces, Exterior Window System, Interior Flooding, Partitions
Risk Category IV – Office	Design	Residual Drift, Interior Flooding, Exterior Window System, Steel Braces
	100% MCE	Residual Drift, Interior Flooding, Steel Braces, Exterior Window System, MEP Components
Risk Category II – Healthcare	Design	Residual Drift, Medical Equipment, Exterior Window System, Steel Braces, Interior Flooding
	100% MCE	Residual Drift, Medical Equipment, Exterior Window System, Steel Braces, Interior Flooding
Risk Category IV – Healthcare	Design	Residual Drift, Medical Equipment, Exterior Window System, Interior Flooding, Steel Braces
	100% MCE	Residual Drift, Medical Equipment, Steel Braces, Interior Flooding, Exterior Window System

The performance of Steel BRBF archetypes is very sensitive to design story drift ratio. Steel BRBF archetypes designed for code maximum story drift ratios are more likely to trigger unrepairable residual drift at higher shaking intensities. Conversely, Steel BRBF systems designed for lower story drift ratios show significant improvement in performance.

Higher design forces and lower story drift ratios associated with Risk Category IV design requirements, as well as higher design forces and enhanced detailing requirements for nonstructural components, have the effect of reducing structural damage, unrepairable residual drift, and potential for nonstructural damage in Steel BRBF archetypes.

The effect of changes in design story drift ratio can be seen in Figure 5-5, which shows median repair costs on the design space for Steel BRBF, Risk Category II and IV, office archetypes, subjected to design earthquake (67% MCE) shaking intensity, averaged over all building heights and hazards levels. In the figure, average median repair costs for Steel BRBF archetypes are strongly influenced by design story drift ratio, and archetypes with smaller design story drift ratios have significantly lower average median repair costs. Reductions due to Risk Category IV criteria are less significant in comparison with other systems because assumed design story drifts for certain Steel BRBF archetypes have already been conservatively reduced, and taken as less than code maxima across the design space.

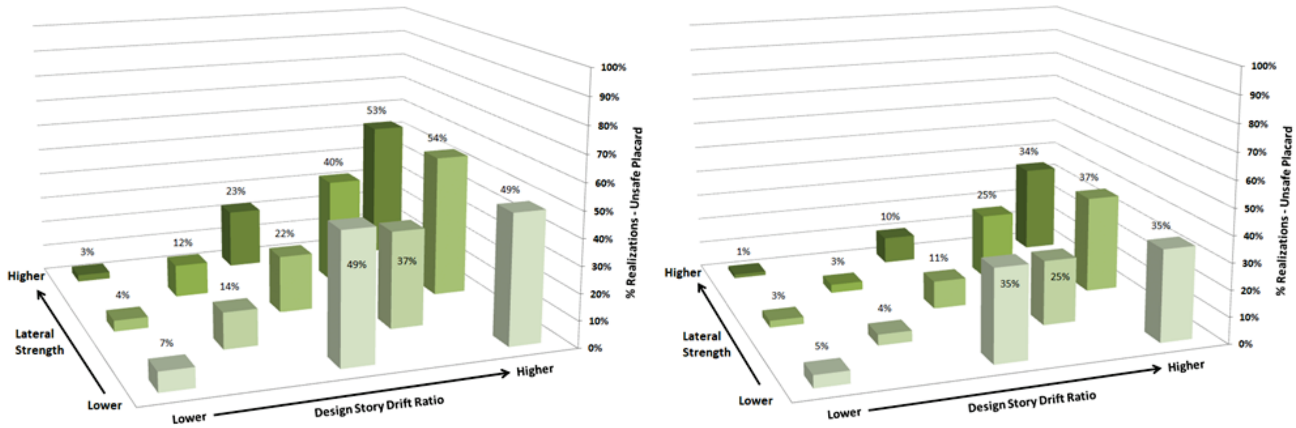


Repair Cost, Risk Category II, Office, 67% MCE

Repair Cost, Risk Category IV, Office, 67% MCE

Figure 5-5 Median repair costs for 13 lateral strength/design story drift ratio combinations, Steel BRBF, Risk Category II and IV, office occupancies, 67% MCE.

Figure 5-6 shows the probability of triggering an unsafe placard on the design space for Steel BRBF, Risk Category II and IV, office archetypes, subjected to design earthquake (67% MCE) shaking intensity, averaged over all building heights and hazards levels. Trends for the average probability of triggering an unsafe placard in Steel BRBF archetypes are the same as observed for median repair costs.

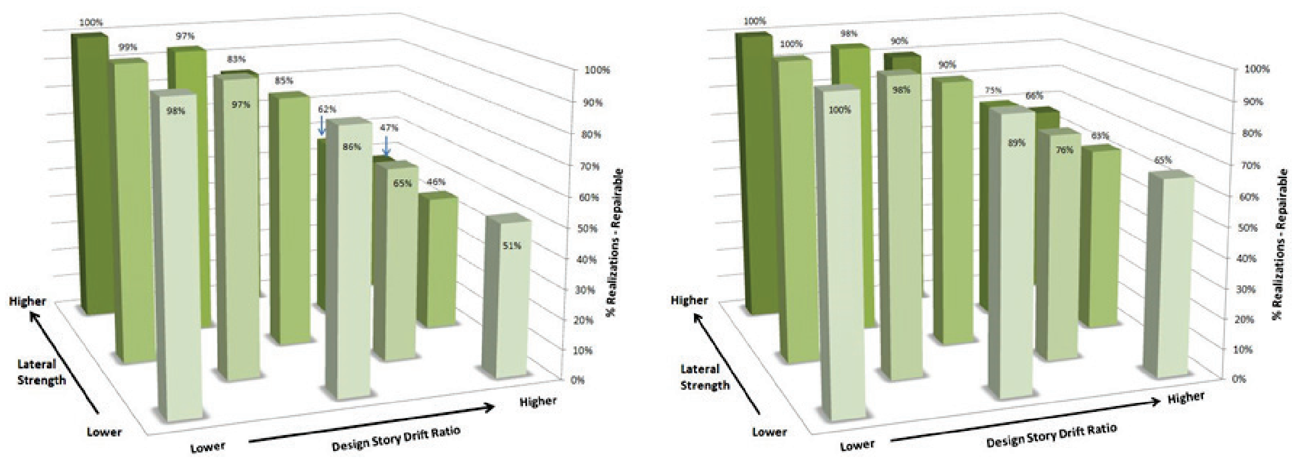


Unsafe Placard, Risk Category II, Office, 67% MCE

Unsafe Placard, Risk Category IV, Office, 67% MCE

Figure 5-6 Probability of incurring an unsafe placard for 13 lateral strength/design story drift ratio combinations, Steel BRBF, Risk Category II and IV, office occupancies, 67% MCE.

Figure 5-7 shows repairability on the design space for Steel BRBF, Risk Category II, office archetypes, subjected to design earthquake (67% MCE) shaking intensity, averaged over all building heights and hazards levels. Note that, in contrast with other performance metrics, repairability is a positive metric and higher values indicate better performance.



Repairability, Risk Category II, Office, 67% MCE

Repairability, Risk Category IV, Office, 67% MCE

Figure 5-7 Repairability for 13 lateral strength/design story drift ratio combinations, Steel BRBF, Risk Category II and IV, office occupancies, 67% MCE.

In the figure, trends observed in average repairability for Steel BRBF archetypes show similar dependence on design story drift ratio and less dependence on design strength and Risk Category. Bars approaching 100%

average repairability show that high-performing Steel BRBF systems occur within the design space at drift ratios less than code maximum drift limits.

In the case of other performance metrics, average median repair times showed the same dependency on lateral strength and design story drift ratio as observed for repair costs. Casualty risk in Steel BRBF archetypes, however, was not significantly influenced by lateral strength or design story drift ratio.

5.3.4 Steel Special Concentrically-Braced Frames

Median results for Steel special concentrically-braced frame (SCBF) systems, averaged across all Steel SCBF archetype strength and stiffness combinations, heights, and hazard levels, are summarized in Table 5-8.

Table 5-8 Average Performance of Steel Special Concentrically-Braced Frame Systems – Median Results

Performance Measure	Performance at Each Intensity Level				
	20%	40%	Design	80%	MCE
Risk Category II – Office					
Repair Cost	2%	9%	16%	24%	39%
Repair Time	9 days	27 days	41 days	77 days	188
Casualty Rate	0%	0.4%	2.0%	3.1%	4.2%
Probability of Unsafe Placard	5%	29%	54%	65%	74%
Repairability	100%	100%	99%	97%	93%
Risk Category II – Healthcare (Medical Office Building or Laboratory)					
Repair Cost	4%	16%	28%	35%	46%
Repair Time	13 days	44 days	69 days	83 days	165
Casualty Rate	0%	0.5%	2.3%	3.4%	4.6%
Probability of Unsafe Placard	4%	26%	51%	63%	73%
Repairability	98%	93%	84%	77%	67%
Risk Category IV – Office (Emergency Operations Center)					
Repair Cost	1%	6%	12%	15%	18%
Repair Time	3 days	20 days	34 days	41 days	48 days
Casualty Rate	0%	0.3%	1.7%	2.8%	4.1%
Probability of Unsafe Placard	1%	15%	40%	52%	63%
Repairability	100%	100%	99%	98%	93%
Risk Category IV – Healthcare (Hospital)					
Repair Cost	1%	7%	14%	17%	21%
Repair Time	4 days	23 days	41 days	50 days	58 days
Casualty Rate	0%	0.3%	1.8%	3.0%	4.3%
Probability of Unsafe Placard	1%	14%	39%	52%	64%
Repairability	100%	99%	98%	97%	91%

As observed in other systems, losses in Steel SCBF systems increase, and repairability decreases, as the intensity of shaking increases. Because buckling of braces initiates at relatively low drift levels, median losses in SCBF systems are driven by damage to braces, which is common at 40% MCE and stronger shaking intensities. Steel SCBF archetypes also experience higher floor accelerations in comparison with other more flexible systems, which results in increased occurrence of damage to acceleration-controlled nonstructural components.

Between Risk Categories, losses in Steel SCBF systems are lower, and repairability of Steel SCBF systems is higher, for Risk Category IV archetypes relative to Risk Category II archetypes, in both office and healthcare occupancies. Within a given Risk Category, losses in Steel SCBF archetypes for healthcare occupancies are somewhat higher than office occupancies because of the presence of additional, high-value equipment and increased (24-hour) occupancy associated with healthcare occupancies.

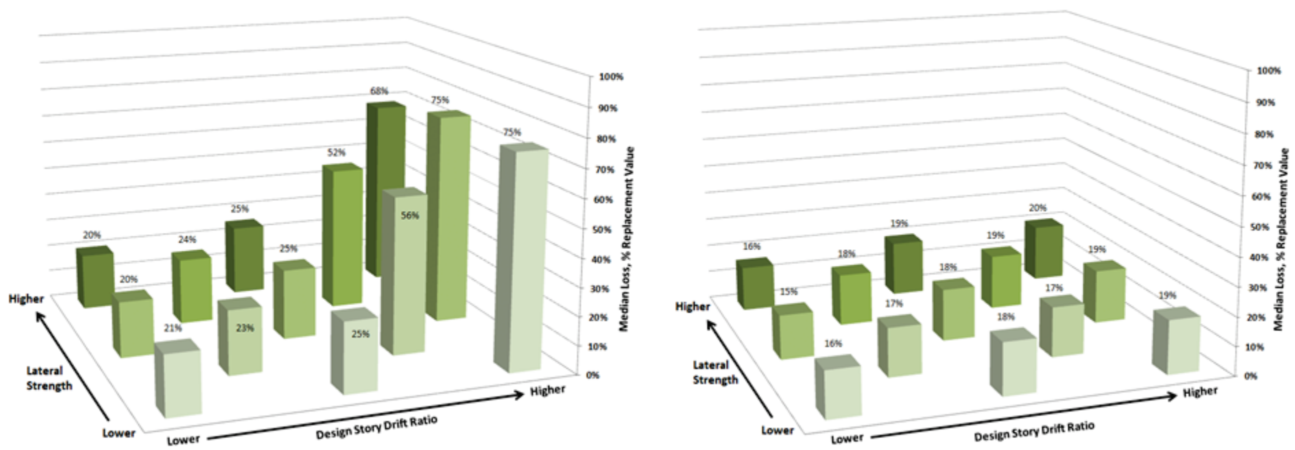
Components contributing most significantly to losses in Steel SCBF, Risk Category II and IV, office and healthcare archetypes are listed in Table 5-9, in decreasing order of importance.

Table 5-9 Components Contributing to Losses, Steel Special Concentrically-Braced Frame Systems

Occupancy and Risk Category	Intensity Level	Components Contributing to Losses
Risk Category II – Office	Design	Steel Braces, Interior Flooding, Ceilings, Residual Drift
	100% MCE	Steel Braces, Residual Drift, Interior Flooding, Ceilings, Exterior Window System
Risk Category IV – Office	Design	Steel Braces, Interior Flooding, MEP Systems, Ceilings, Exterior Window System
	100% MCE	Steel Braces, Interior Flooding, Ceilings, Exterior Window System, MEP Systems
Risk Category II – Healthcare	Design	Medical Equipment, Steel Braces, Interior Flooding, Exterior Window Systems, Ceilings
	100% MCE	Medical Equipment, Steel Braces, Residual Drift, Interior Flooding, Exterior Window System, Ceilings
Risk Category IV – Healthcare	Design	Medical Equipment, Steel Braces, Interior Flooding, Exterior Window Systems, Ceilings
	100% MCE	Medical Equipment, Steel Braces, Interior Flooding, Residual Drift, Exterior Window System, Ceilings

Brace damage is a major contributor to losses in Steel SCBF systems for both Risk Category II and Risk Category IV archetypes. Other significant contributors to loss include residual drift, interior flooding, exterior window systems, and damage to acceleration-controlled components, such as ceiling systems and mechanical, electrical, and plumbing equipment. Other less significant contributors to loss (not listed in Table 5-9) include partitions and elevators.

Figure 5-8 shows median repair costs on the design space for Steel SCBF, Risk Category II and IV, office archetypes, subjected to 100% MCE shaking intensity, averaged over all building heights and hazards levels. In the figure, average median repair costs for Steel SCBF archetypes decrease significantly as the design story drift ratio decreases across the design space, while variations in lateral strength had comparatively little influence. Reductions occur across the entire design space under more stringent Risk Category IV design requirements, showing little variation with strength and stiffness. A similar trend is observed for average median repair times across the design space for Steel SCBF archetypes.



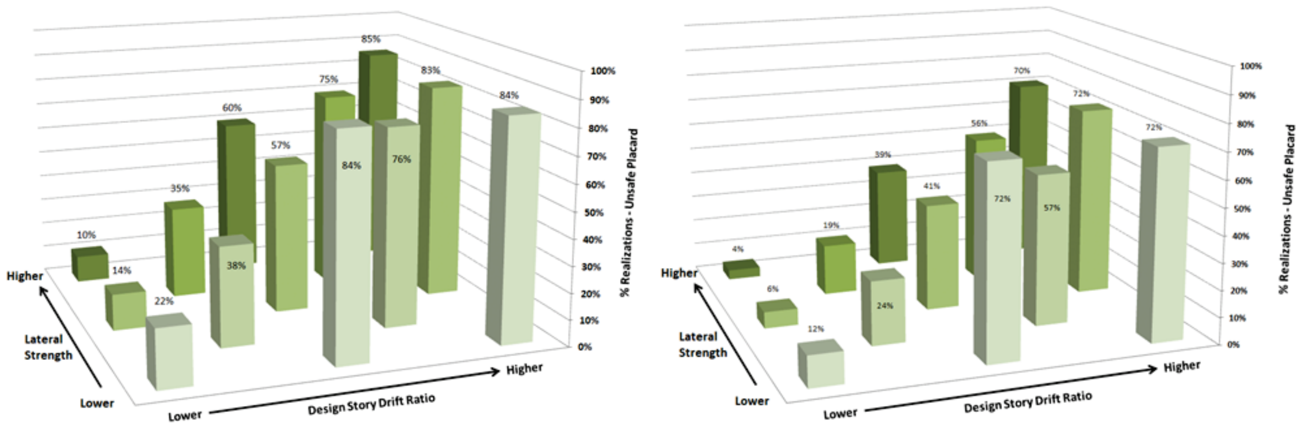
Repair Cost, Risk Category II, Office, 100% MCE

Repair Cost, Risk Category IV, Office, 100% MCE

Figure 5-8 Median repair costs for 13 lateral strength/design story drift ratio combinations, Steel SCBF, Risk Category II and IV, office occupancies, 100% MCE.

Although Risk Category IV criteria include higher design forces and lower design story drift ratios, engineering practice is expected to result in designs that are significantly stiffer that required, and design story drifts have been conservatively taken as less than code maximum drift limits in both Risk Category II and Risk Category IV Steel SCBF archetypes (see Tables 2-5 and 2-6). As a result, Steel SCBF archetypes benefit less from more restrictive Risk Category IV drift criteria than other systems. Risk Category IV design requirements reduce, but do not eliminate, damage to nonstructural components in Steel SCBF systems. Interior flooding still contributes significantly to losses in Risk Category IV. Also, higher strength and stiffness in Steel SCBF, Risk Category IV archetypes results in higher floor accelerations, which reduces some of the benefit that higher bracing and anchorage forces on nonstructural components can have on reducing losses.

Figure 5-9 shows the probability of triggering an unsafe placard on the design space for Steel SCBF, Risk Category II and IV, office archetypes, subjected to design earthquake (67% MCE) shaking intensity, averaged over all building heights and hazards levels. In the figure, average probabilities of triggering an unsafe placard are strongly influenced by design story drift ratio, and somewhat influenced by lateral strength. Archetypes with higher lateral strengths and smaller design story drift ratios are less likely to trigger an unsafe placard.



Unsafe Placard, Risk Category II, Office, 67% MCE

Unsafe Placard, Risk Category IV, Office, 67% MCE

Figure 5-9 Probability of incurring an unsafe placard for 13 lateral strength/design story drift ratio combinations, Steel SCBF, Risk Category II and IV, office occupancies, 67% MCE.

For reasons noted above, overall probabilities of triggering an unsafe placard are not that strongly influenced by Risk Category. In general, Risk Category IV Steel SCBF archetypes showed only marginal improvement in performance over Risk Category II Steel SCBF archetypes across all performance metrics.

5.3.5 Special Reinforced Concrete Shear Walls

Median results for special reinforced concrete shear wall (Special RCSW) systems, averaged across all Special RCSW archetype strength and stiffness combinations, heights, and hazard levels, are summarized in Table 5-10.

As observed in other systems, losses in Special RCSW systems increase, and repairability decreases, as the intensity of shaking increases. Between Risk Categories, losses in Special RCSW systems are lower, and repairability of Special RCSW systems is higher, for Risk Category IV buildings relative to Risk Category II buildings, in both office and healthcare occupancies. Within a given Risk Category, losses in Special RCSW archetypes for healthcare occupancies are higher than office occupancies because of the presence of additional, high-value equipment and increased (24-hour) occupancy associated with healthcare occupancies.

Table 5-10 Average Performance of Special Reinforced Concrete Shear Wall Systems – Median Results

Performance Measure	Performance at Each Intensity Level				
	20%	40%	Design	80%	MCE
Risk Category II – Office					
Repair Cost	0%	1%	4%	6%	9%
Repair Time	0 days	7 days	18 days	24 days	31 days
Casualty Rate	0%	0%	0.4%	0.9%	1.6%
Probability of Unsafe Placard	0%	1%	8%	15%	27%
Repairability	100%	100%	100%	99%	97%
Risk Category II – Healthcare (Medical Office Building or Laboratory)					
Repair Cost	0%	6%	17%	23%	28%
Repair Time	2 days	19 days	41 days	52 days	64 days
Casualty Rate	0%	0%	0.4%	0.8%	1.5%
Probability of Unsafe Placard	0%	0%	4%	9%	20%
Repairability	99%	95%	88%	82%	76%
Risk Category IV – Office (Emergency Operations Center)					
Repair Cost	0%	1%	4%	6%	7%
Repair Time	0 days	5 days	15 days	19 days	23 days
Casualty Rate	0%	0%	0.2%	0.5%	1.1%
Probability of Unsafe Placard	0%	0%	1%	4%	11%
Repairability	100%	100%	100%	100%	99%
Risk Category IV – Healthcare (Hospital)					
Repair Cost	0%	1%	5%	7%	10%
Repair Time	0 days	6 days	20 days	56 days	31 days
Casualty Rate	0%	0%	0.2%	0.5%	1.1%
Probability of Unsafe Placard	0%	0%	1%	4%	11%
Repairability	100%	100%	99%	99%	98%

Components contributing most significantly to losses in Special RCSW, Risk Category II and IV, office and healthcare archetypes are listed in Table 5-11, in decreasing order of importance. Median losses in Special RCSW systems are driven by damage to concrete elements and acceleration-sensitive components including interior flooding, ceilings, mechanical, electrical, and plumbing systems, and medical equipment. Other less significant contributors to loss (not listed in Table 5-11) include concrete structural elements in low-rise archetypes, and concrete shear walls and flat slab/column components in high-rise archetypes.

Table 5-11 **Components Contributing to Losses, Special Reinforced Concrete Shear Wall Systems**

Occupancy and Risk Category	Intensity Level	Components Contributing to Losses
Risk Category II – Office	Design	Interior Flooding, MEP Systems, Ceilings
	100% MCE	Interior Flooding, Ceilings, MEP Systems
Risk Category IV – Office	Design	Interior Flooding, Ceilings, MEP Systems
	100% MCE	Interior Flooding, Ceilings, MEP Systems
Risk Category II – Healthcare	Design	Medical Equipment, Interior Flooding, MEP Systems
	100% MCE	Medical Equipment, Interior Flooding, MEP Systems
Risk Category IV – Healthcare	Design	Medical Equipment, Interior Flooding, MEP Systems
	100% MCE	Medical Equipment, Interior Flooding, MEP Systems

Figure 5-10 shows median repair costs on the design space for Special RCSW, Risk Category II and IV, office archetypes, subjected to 100% MCE shaking intensity, averaged over all building heights and hazards levels. In the figure, average median repair costs for Special RCSW archetypes are relatively low and change very little across the design space, indicating that variations in lateral strength and design story drift ratio had limited influence on repair costs.

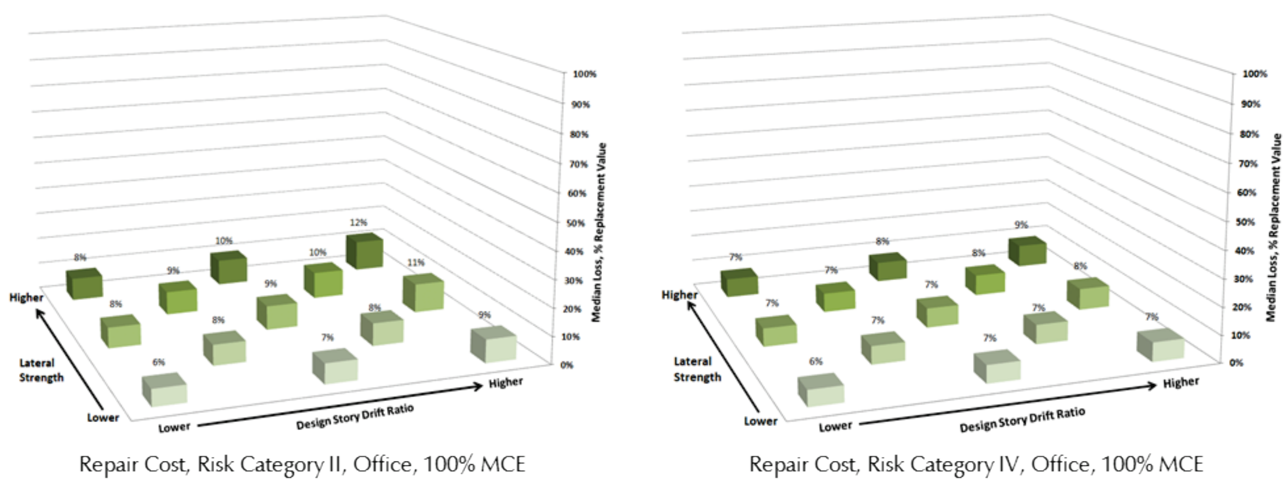
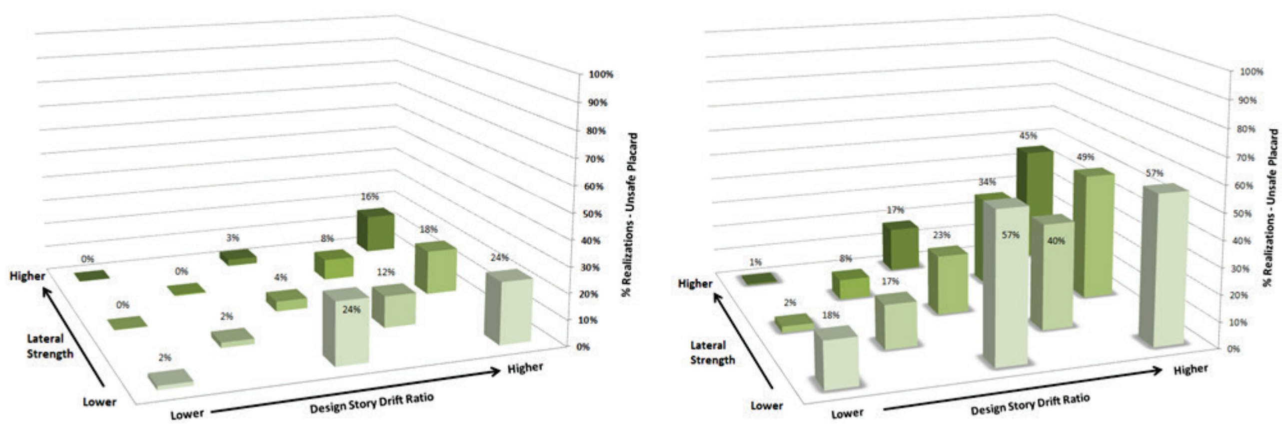


Figure 5-10 Median repair costs for 13 lateral strength/design story drift ratio combinations, Special RCSW, Risk Category II and IV, office occupancies, 100% MCE.

Reductions in average median repair costs for Risk Category IV archetypes showed only marginal improvement over Risk Category II archetypes. Although Risk Category IV criteria include higher design forces and lower design story drift ratios, engineering practice is expected to result in designs that are significantly stiffer that required, and design story drifts for Special RCSW archetypes have been conservatively taken as less than code maximum drift limits in both Risk Category II and Risk Category IV archetypes (see Tables 2-5 and 2-6). As a result, Special RCSW archetypes benefit less from more restrictive Risk Category IV drift criteria than other systems.

Risk Category IV design requirements reduce, but do not eliminate, damage to nonstructural components in Special RCSW archetypes. Interior flooding still contributes significantly to losses in Risk Category IV archetypes. Also, higher strength and stiffness in Risk Category IV Special RCSW systems results in higher floor accelerations, which reduces some of the benefit that higher bracing and anchorage forces on nonstructural components can have on reducing losses. Similar trends were observed for other performance metrics, including median repair times, casualty rates, and repairability.

Figure 5-11 shows the probability of triggering an unsafe placard on the design space for Special RCSW, Risk Category II, office archetypes, subjected to design earthquake (67% MCE) and 100% MCE shaking intensity, averaged over all building heights and hazards levels.



Unsafe Placard, Risk Category II, Office, 67% MCE

Unsafe Placard, Risk Category II, Office, 100% MCE

Figure 5-11 Probability of incurring an unsafe placard for 13 lateral strength/design story drift ratio combinations, Special RCSW, Risk Category II, office occupancies, 67% MCE and 100% MCE.

In the figure, average probabilities of triggering an unsafe placard are significantly influenced by lateral strength and design story drift ratio. Archetypes designed for code-minimum lateral strength are substantially more likely to trigger an unsafe placard, unless they are also designed for lower story drift ratios. In comparing design earthquake versus MCE shaking intensities, the trend is more pronounced at 100% MCE shaking. The probability of triggering an unsafe placard rises significantly, even at low design story drift ratios, as the intensity changes from 67% MCE to 100% MCE. This is attributed to damage to concrete shear walls and flat slab-column connections in MCE shaking intensities.

5.4 Performance Assessment Results by Metric

Archetypes in each system were evaluated for each of five performance metrics: repair costs, repair time, casualty rate, probability of unsafe placard, and repairability. Performance assessment results are reported for each metric, separated by Risk Category and occupancy, based on representative designs in each system.

5.4.1 Repair Cost

Repair cost is the cost to restore damaged components to their pre-earthquake condition, expressed as a percentage of the replacement value of the building. Repair costs do not include other costs such as loss of income due to business interruption, the cost to identify, plan, and permit repairs, or the cost of financing repairs.

Repair costs are accumulated in each realization based on the damage sustained by each component, provided collapse has not occurred and the building has not been deemed a total loss due to residual story drift. If, in a given realization, the building collapses or the maximum residual drift ratio renders the building unrepairable, then the total replacement cost is assigned to the realization.

Average median repair costs for each system are summarized in Table 5-12. Values in the table are based on representative design points for each system, averaged across all hazard levels (Low SDC D, SDC D, and SDC E/F) and building heights (low-, mid-, and high-rise). Overall, average median repair costs increase with shaking intensity, although the magnitude of the values, and the magnitude of the increase, differs between systems.

Average median repair costs are higher, and the rate of increase with intensity is more significant in systems identified in Section 5.3 to be more sensitive to residual drift. These include Steel BRBF and Steel SCBF systems that showed sensitivity to increases in drift demand, along with limited capacity for overstrength beyond the design strength. Although losses in drift-controlled systems (e.g., Steel SMRF and RC SMRF systems) also include contributions from residual drift, average median repair costs are lower due to indirect contributions to overstrength caused by proportioning structural members for increased stiffness. Stiff, strength-controlled systems (e.g., Special RCSW systems) exhibited lower average median repair costs overall, and less sensitivity to increases in shaking intensity, but higher proportions of nonstructural damage (e.g., interior flooding) due to higher floor accelerations.

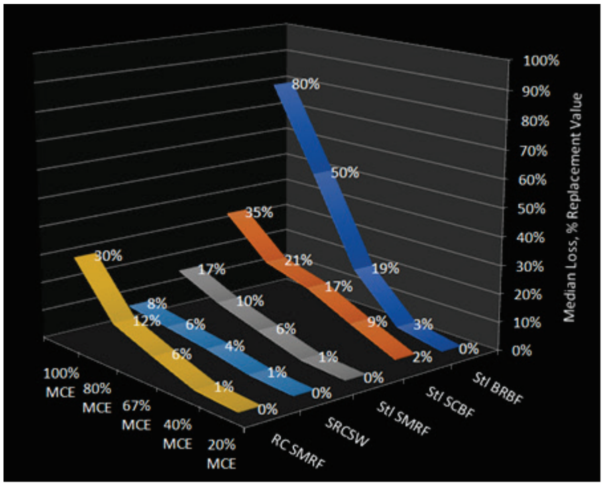
Table 5-12 Average Repair Costs for Representative Designs – Median Results

Seismic Force-Resisting System	Repair Cost (% of Replacement Value)				
	20%	40%	Design	80%	MCE
Risk Category II – Office					
Steel SMRF	0%	1%	6%	10%	17%
RC SMRF	0%	1%	6%	12%	30%
Steel BRBF	0%	3%	19%	50%	80%
Steel SCBF	2%	9%	17%	21%	35%
Special RCSW	0%	1%	4%	6%	8%
Risk Category II – Healthcare (Medical Office Building or Laboratory)					
Steel SMRF	0%	3%	13%	22%	33%
RC SMRF	0%	3%	14%	24%	49%
Steel BRBF	1%	9%	34%	62%	86%
Steel SCBF	3%	17%	28%	34%	46%
Special RCSW	0%	7%	17%	23%	29%
Risk Category IV – Office (Emergency Operations Center)					
Steel SMRF	0%	0%	3%	5%	8%
RC SMRF	0%	0%	3%	5%	7%
Steel BRBF	0%	2%	9%	40%	56%
Steel SCBF	1%	6%	12%	15%	17%
Special RCSW	0%	1%	4%	5%	7%
Risk Category IV – Healthcare (Hospital)					
Steel SMRF	0%	1%	5%	8%	12%
RC SMRF	0%	1%	5%	8%	12%
Steel BRBF	0%	4%	22%	45%	59%
Steel SCBF	1%	8%	16%	20%	23%
Special RCSW	0%	2%	8%	12%	16%

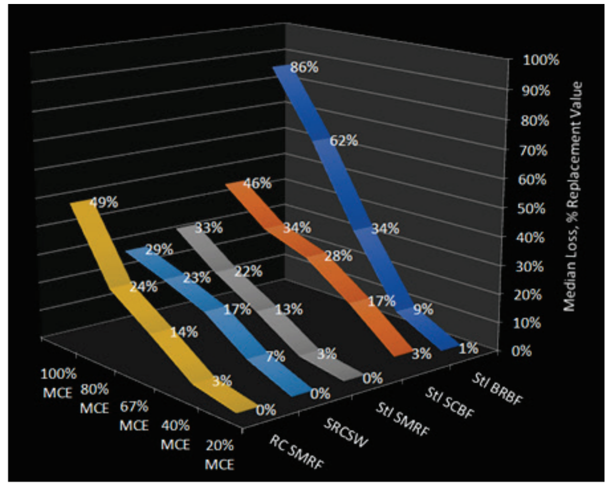
A comparison of median repair costs for each system, separated by Risk Category and occupancy, is shown in Figure 5-12. In general, trends in relative losses between systems, and the change in losses with shaking intensity, are consistent across changes in occupancy and Risk Category.

Within a given Risk Category, repair costs for healthcare occupancies are somewhat higher than office occupancies. This is attributed to the presence of high-value medical equipment and increased (24-hour) occupancy associated with healthcare occupancies.

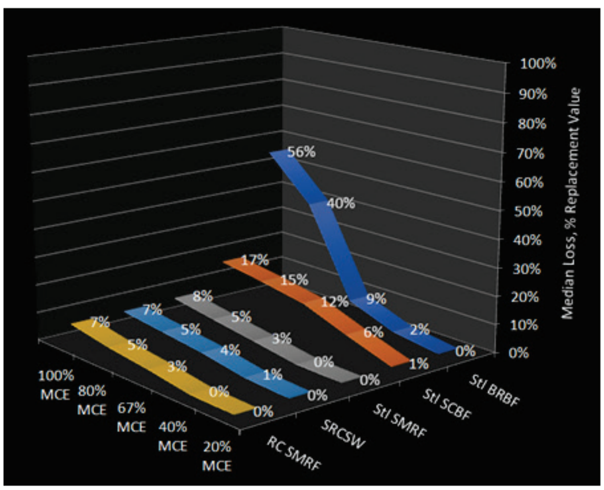
Between Risk Categories, repair costs for Risk Category IV archetypes are significantly lower than Risk Category II archetypes over all shaking intensities, although the magnitude of the difference varies between systems. This is attributed to the relative effects of designing Risk Category IV structures for higher lateral forces and lower story drift ratios than Risk Category II structures.



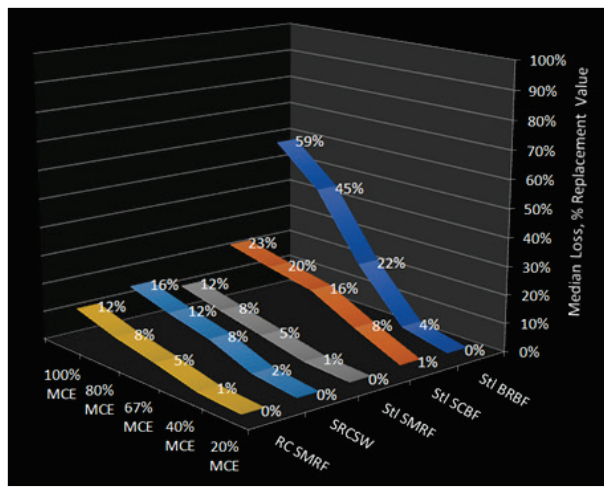
Risk Category II, Office



Risk Category II, Healthcare



Risk Category IV, Office



Risk Category IV, Healthcare

Figure 5-12 Comparison of median repair costs for each system, separated by Risk Category and occupancy, average of representative designs.

The following system-specific observations on average median repair costs are made:

- Steel SMRF systems – Exterior window systems and partitions are significant contributors to losses in Risk Category II archetypes; Risk Category IV archetypes benefit from reduced design story drift ratios.

- RC SMRF systems – Exterior window systems and partitions are significant contributors to losses in Risk Category II archetypes; Risk Category IV archetypes benefit from reduced design story drift ratios; damage to concrete beams and flat slab/column connections are significant contributors to losses at higher shaking intensities.
- Steel BRBF systems –Risk Category IV archetypes benefit from reduced design story drift ratios, although at design earthquake (67% MCE) and higher shaking intensities, the potential for residual drift significantly increases losses.
- Steel SCBF systems – Brace damage, which initiates at low shaking intensities, is a significant contributor to losses in both Risk Category II and Risk Category IV archetypes.
- Special RCSW systems – Interior flooding is a significant contributor to losses in stronger, stiffer archetypes; damage to concrete beams and flat slab/column connections is a significant contributor to losses at higher shaking intensities.

5.4.2 Repair Time

Repair time is the number of days required to restore damaged components to their pre-earthquake condition. Repair time does not include additional time required to identify, plan, and permit the work, arrange financing, or hire and mobilize contractors.

To estimate repair time, each damage state includes a time-related consequence function that indicates the number of labor hours associated with specified repair actions. In the FEMA P-58 methodology, calculation of repair time can consider serial (i.e., sequential) or parallel repair strategies. Neither strategy is expected to represent the actual schedule of repairs, but the two extremes are intended to represent an upper and lower bound. In this study, parallel repair strategies have been assumed, which considers repair work occurring on all floors simultaneously, and represents a possible lower-bound repair time. Repair time is also influenced by the estimated number of workers performing repairs at a given time. In the FEMA P-58 methodology, this is controlled by the “maximum workers per square foot” parameter, which was set to the recommended default value. If in a realization a building is deemed a total loss due to collapse or irreparable residual drift, the repair time is set to 720 days, representing building replacement.

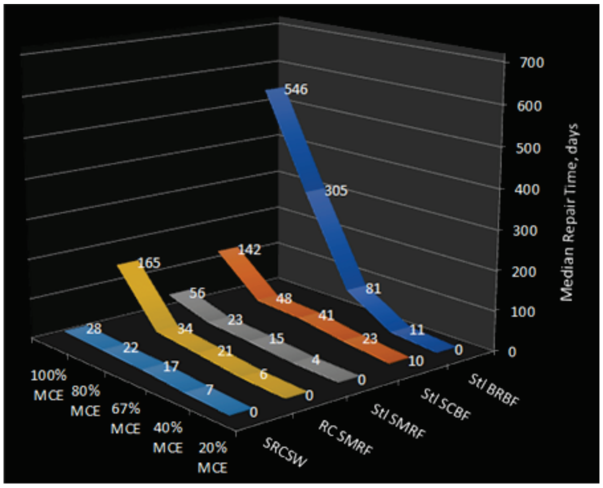
Median repair times for each system are summarized in Table 5-13. Values in the table are based on representative design points for each system, averaged across all hazard levels (Low SDC D, SDC D, and SDC E/F) and building heights (low-, mid-, and high-rise).

Table 5-13 Average Repair Times for Representative Designs – Median Results

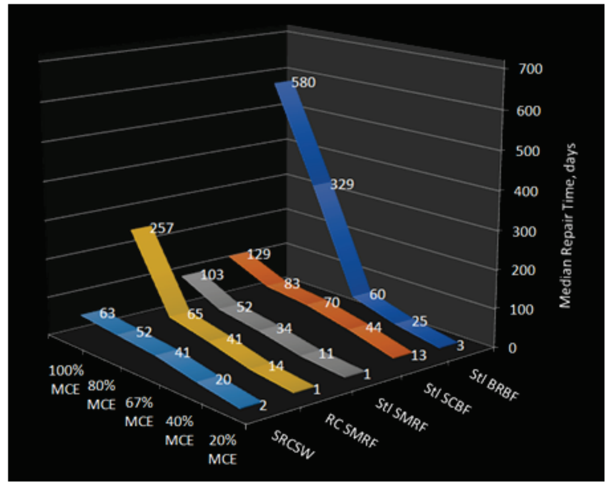
Seismic Force-Resisting System	Repair Time (Days)				
	20%	40%	Design	80%	MCE
Risk Category II – Office					
Steel SMRF	0	4	15	23	56
RC SMRF	0	6	21	34	165
Steel BRBF	0	11	81	305	546
Steel SCBF	10	23	41	48	142
Special RCSW	0	7	17	22	28
Risk Category II – Healthcare (Medical Office Building or Laboratory)					
Steel SMRF	1	11	34	52	103
RC SMRF	1	14	41	65	257
Steel BRBF	3	25	60	329	580
Steel SCBF	13	44	70	83	129
Special RCSW	2	20	41	52	63
Risk Category IV – Office (Emergency Operations Center)					
Steel SMRF	0	3	11	18	23
RC SMRF	0	3	12	19	25
Steel BRBF	0	8	25	259	376
Steel SCBF	2	21	33	41	47
Special RCSW	0	5	15	18	22
Risk Category IV – Healthcare (Hospital)					
Steel SMRF	0	6	24	35	47
RC SMRF	0	7	25	36	49
Steel BRBF	1	18	84	278	395
Steel SCBF	6	34	59	72	82
Special RCSW	0	12	31	41	52

Overall, average median repair times in Table 5-13 increase with shaking intensity, although the magnitude of the values, and the magnitude of the increase, differs between systems. Because repair times are proportional to repair costs, the relative trends in median repair times between systems are similar to trends reported for repair costs in Section 5.4.1.

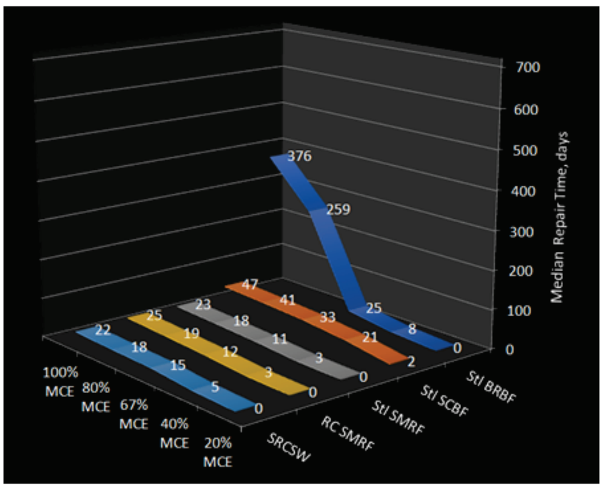
A comparison of median repair times for each system, separated by risk category and occupancy, is shown in Figure 5-13. In general, trends in relative losses between systems, and the change in losses with shaking intensity, are consistent across changes in occupancy and Risk Category.



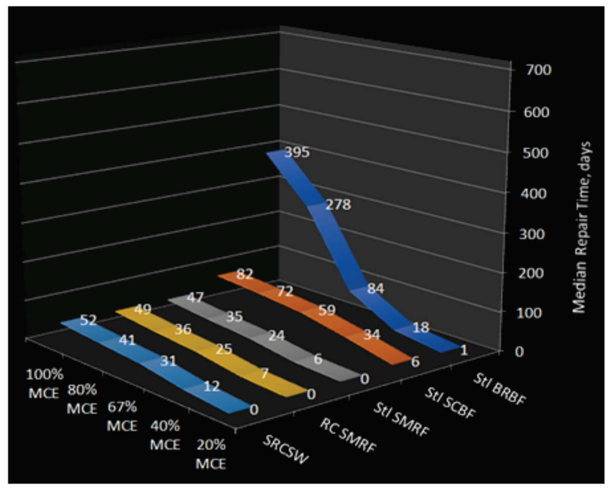
Risk Category II, Office



Risk Category II, Healthcare



Risk Category IV, Office



Risk Category IV, Healthcare

Figure 5-13 Comparison of median repair times for each system, separated by Risk Category and occupancy, average of representative designs.

Within a given Risk Category, repair costs for healthcare occupancies are somewhat higher than office occupancies. This is attributed to the presence of high-value medical equipment and increased (24-hour) occupancy associated with healthcare occupancies. Although the time to repair individual medical components was assumed to be relatively short, the large number of components present in healthcare occupancies impacted overall repair times.

Between Risk Categories, repair costs for Risk Category IV archetypes are lower than Risk Category II archetypes over all shaking intensities, although the magnitude of the difference varies between systems. This is attributed to the relative effects of designing Risk Category IV structures for higher lateral forces and lower story drift ratios than Risk Category II structures.

The following system-specific observations on average median repair times are made:

- Steel SMRF systems –Risk Category IV archetypes benefit from reduced design story drift ratios on the structural system and higher design forces on nonstructural components.
- RC SMRF systems –Risk Category IV archetypes benefit from reduced design story drift ratios on the structural system and higher design forces on nonstructural components.
- Steel BRBF systems – Repair times are comparable to other systems up to the design earthquake (67% MCE), but at higher shaking intensities, an increased potential for residual drift significantly increases repair times relative to other systems.
- Steel SCBF systems – Brace damage, which initiates at low shaking intensities, interior flooding, and equipment damage are significant contributors to repair times in both Risk Category II and Risk Category IV archetypes.
- Special RCSW systems – Repair times are generally less than other systems across all intensities, occupancies, and Risk Categories.

The FEMA P-58 methodology identifies damage to components with long lead times, which generally includes complex items, such as elevator systems, and major mechanical equipment, such as chillers, cooling towers, and air handlers. The time to procure long lead time items, however, is not included in repair time estimates, because lead times are highly variable, and are case-specific. In addition to the time it might take to repair or replace a component, it could take additional weeks to months to acquire components for long lead time items. The following trends in the results for long lead time items were observed:

- For Risk Category II archetypes, long lead time flags triggered for mechanical/electrical/plumbing equipment in approximately 20% of realizations for Steel SMRF and RC SMRF systems, and approximately 50% of realizations for Steel BRBF, Steel SCBF, and Special RCSW systems, at the design earthquake (67% MCE) shaking intensity.
- For Risk Category IV archetypes, long lead time flags triggered for mechanical/electrical/plumbing equipment in less than 10% of realizations for Steel SMRF and RC SMRF systems, and less than 20% of realizations for Steel BRBF, Steel SCBF, and Special RCSW systems, at the design earthquake (67% MCE) shaking intensity.

- Long lead time flags triggered for elevators in approximately 80% of realizations at the design earthquake (67% MCE) intensity, regardless of Risk Category.

In general, stiffer systems triggered acceleration-controlled long lead time items more frequently than flexible systems due to higher floor accelerations, and Risk Category IV design requirements reduced the potential for long lead time triggers relative to Risk Category II design requirements.

5.4.3 Casualty Rate

Casualty rate is the probability of any one occupant in a building being fatally or seriously injured as a result of an earthquake. The FEMA P-58 methodology reports the number of casualties as a direct output of the Performance Assessment Calculation Tool (PACT). The casualty rate is the number of casualties divided by the number of occupants in a building, summed over all realizations. At high shaking intensities, structural collapse contributes to casualties, but injuries caused by falling hazards from nonstructural components can be significant over a range of intensities.

The frequency of collapse is controlled by collapse fragilities, which are based on an inferred collapse capacity derived from the base shear strength, and a defined probability of collapse given the occurrence of a specified shaking intensity. As described in Section 3.7, the collapse fragility is based on an assumed 5 percent probability of collapse given maximum considered earthquake shaking. A value lower than the ASCE/SEI 7-10 stated collapse safety objective was chosen because a 10 percent probability of collapse overpredicts collapse rates observed in past earthquakes, and archetypes across most of the design space exceeded code minimum strength requirements. As a result, casualty rates reported in this study are lower than would be expected if every building were designed to just meet ASCE/SEI 7-10 minimum base shear requirements.

Median casualty rates by system are summarized in Table 5-14. Results are based on representative design points for each system, averaged across all hazard levels (Low SDC D, SDC D, and SDC E/F) and building heights (low-, mid-, and high-rise).

A comparison of median casualty rates for each system, separated by risk category and occupancy, is shown in Figure 5-14. Overall, median casualty rates vary significantly between systems. In general, trends in relative casualty rates between systems, and the change in casualty rates with shaking intensity, are consistent across changes in occupancy and Risk Category.

Within a given Risk Category, casualty rates for healthcare occupancies and office occupancies are nearly the same. Between Risk Categories, casualty rates for Risk Category IV archetypes are only slightly lower than Risk Category II archetypes over all shaking intensities. Although Risk Category IV structures benefit from more stringent design requirements relative to Risk Category II structures, higher lateral strengths and stiffnesses result in higher floor accelerations, which reduce the relative benefit associated with changes in nonstructural design criteria.

Table 5-14 Average Casualty Rates for Representative Designs – Median Results

Seismic Force-Resisting System	Casualty Rate				
	20%	40%	Design	80%	MCE
Risk Category II – Office					
Steel SMRF	0%	0%	0.2%	0.5%	0.9%
RC SMRF	0%	0%	0.1%	0.4%	0.8%
Steel BRBF	0%	0.2%	1.1%	1.8%	2.7%
Steel SCBF	0%	0.4%	2.0%	3.0%	4.1%
Special RCSW	0%	0%	0.4%	0.9%	1.6%
Risk Category II – Healthcare (Medical Office Building or Laboratory)					
Steel SMRF	0%	0%	0.3%	0.6%	1.0%
RC SMRF	0%	0%	0.2%	0.4%	0.8%
Steel BRBF	0%	0.2%	1.1%	1.9%	2.7%
Steel SCBF	0%	0.5%	2.2%	3.4%	4.5%
Special RCSW	0%	0%	0.4%	0.8%	1.5%
Risk Category IV – Office (Emergency Operations Center)					
Steel SMRF	0%	0%	0.1%	0.2%	0.6%
RC SMRF	0%	0%	0%	0.1%	0.4%
Steel BRBF	0%	0.1%	0.6%	1.1%	2.1%
Steel SCBF	0%	0.3%	1.6%	2.7%	4.0%
Special RCSW	0%	0%	0.3%	0.6%	1.1%
Risk Category IV – Healthcare (Hospital)					
Steel SMRF	0%	0%	0.1%	0.2%	0.6%
RC SMRF	0%	0%	0%	0.1%	0.4%
Steel BRBF	0%	0.1%	0.5%	1.0%	1.8%
Steel SCBF	0%	0.3%	1.5%	2.5%	3.6%
Special RCSW	0%	0%	0.2%	0.5%	1.0%

The following system-specific observations on casualty rates are made:

- Strength-controlled systems (e.g., Steel SCBF, Steel BRBF, and Special RCSW systems) have comparatively higher casualty rates due to higher floor accelerations.

- Drift-controlled systems (e.g., Steel SMRF and RC SMRF systems) have comparatively lower casualty rates.
- Suspended ceiling systems, exterior window systems, and suspended mechanical systems are the most significant contributors to casualties caused by nonstructural components.

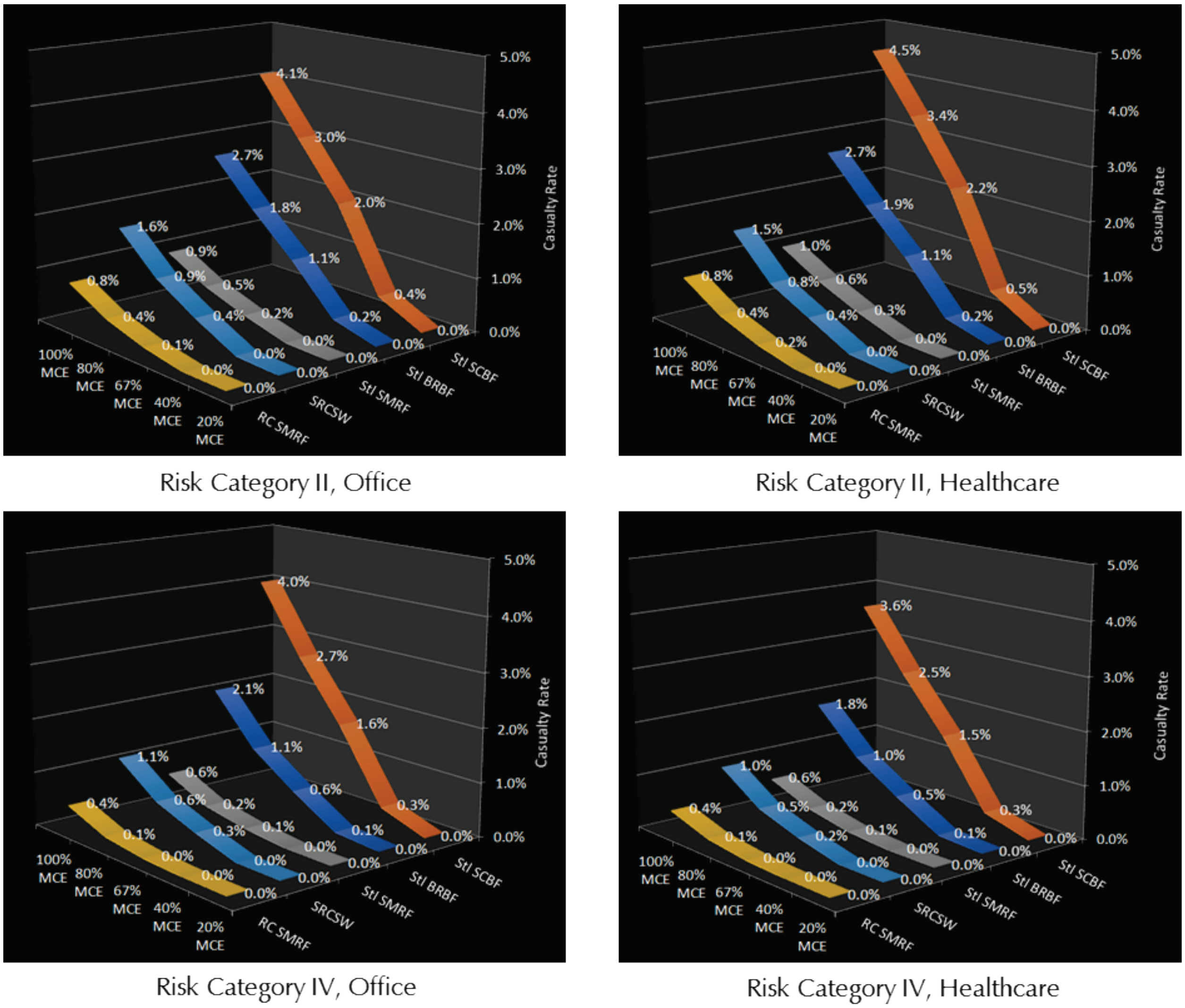


Figure 5-14 Comparison of median casualty rates for each system, separated by Risk Category and occupancy, average of representative designs.

5.4.4 Probability of Unsafe Placard

Probability of Unsafe Placard is the probability that a building will be posted unsafe to occupy following an earthquake, based on the occurrence of structural or nonstructural damage that is considered significant enough to trigger an unsafe posting.

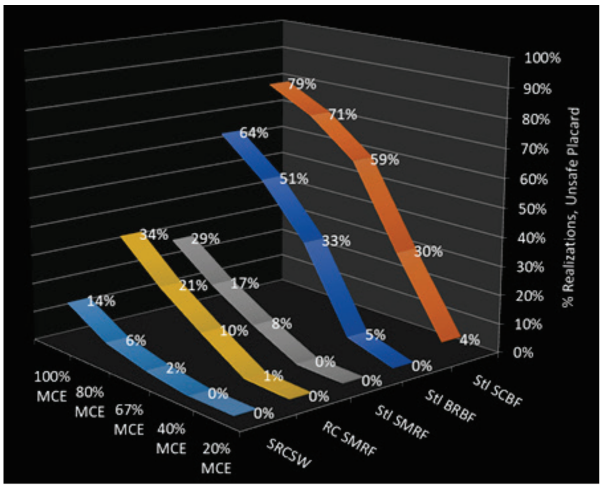
Median probabilities of incurring an unsafe placard by system are summarized in Table 5-15. Results are based on representative design points for each system, averaged across all hazard levels (Low SDC D, SDC D, and SDC E/F) and building heights (low-, mid-, and high-rise).

Table 5-15 Average Probabilities of Incurring an Unsafe Placard for Representative Designs – Median Results

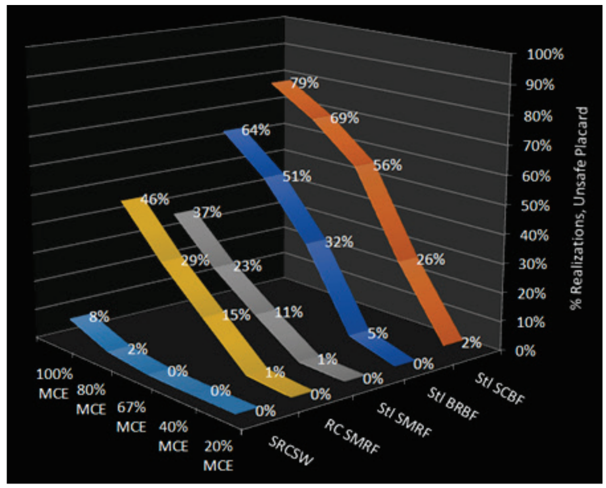
Seismic Force-Resisting System	Probability of Unsafe Placard				
	20%	40%	Design	80%	MCE
Risk Category II – Office					
Steel SMRF	0%	0%	8%	17%	29%
RC SMRF	0%	1%	10%	21%	34%
Steel BRBF	0%	5%	33%	51%	64%
Steel SCBF	4%	30%	59%	71%	79%
Special RCSW	0%	0%	2%	6%	14%
Risk Category II – Healthcare (Medical Office Building or Laboratory)					
Steel SMRF	0%	1%	11%	23%	37%
RC SMRF	0%	1%	15%	29%	46%
Steel BRBF	0%	5%	32%	51%	64%
Steel SCBF	2%	26%	56%	69%	79%
Special RCSW	0%	0%	0%	2%	8%
Risk Category IV – Office (Emergency Operations Center)					
Steel SMRF	0%	0%	1%	5%	14%
RC SMRF	0%	0%	1%	4%	11%
Steel BRBF	0%	2%	20%	34%	50%
Steel SCBF	1%	15%	42%	57%	68%
Special RCSW	0%	0%	0%	0%	2%
Risk Category IV – Healthcare (Hospital)					
Steel SMRF	0%	0%	1%	5%	14%
RC SMRF	0%	0%	1%	4%	12%
Steel BRBF	0%	2%	20%	34%	50%
Steel SCBF	1%	15%	42%	56%	69%
Special RCSW	0%	0%	0%	0%	2%

An unsafe placard (i.e., red tag) is one possible result of a post-earthquake inspection procedure in which a building is deemed to have sustained damage to the point that entry, use, or occupancy poses an immediate risk to safety, and that use may be restricted or prohibited until repairs have been made. Post-earthquake safety inspections are typically rapid visual evaluations, based on limited information, with significant reliance on judgment in determining a final posting. Inspectors have varying degrees of knowledge or experience, may have limited access to the building interior, and may not be able to see damage to structural elements due to the presence of architectural finishes. In contrast, FEMA P-58 assessments identify and report every instance of damage triggering an unsafe placard. As a result, the probability of an unsafe placard, as reported by the FEMA P-58 methodology, can be viewed as an upper bound relative to post-earthquake inspection results observed in past earthquakes.

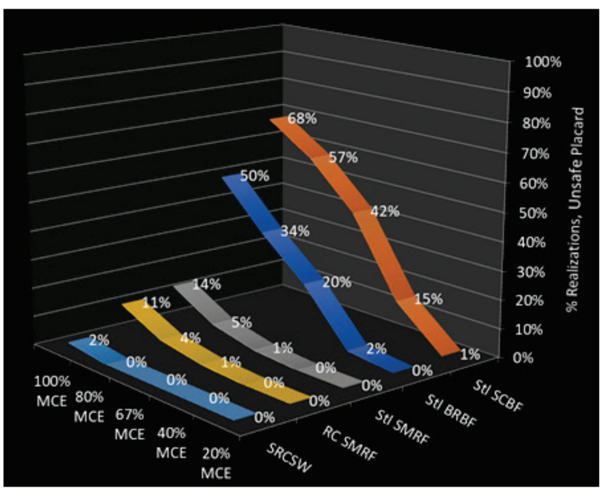
A comparison of median probabilities of incurring an unsafe placard for each system, separated by risk category and occupancy, is shown in Figure 5-15. Results are based on the average of representative design points, across all hazard levels (Low SDC D, SDC D, and SDC E/F) and building heights (low-, mid-, and high-rise).



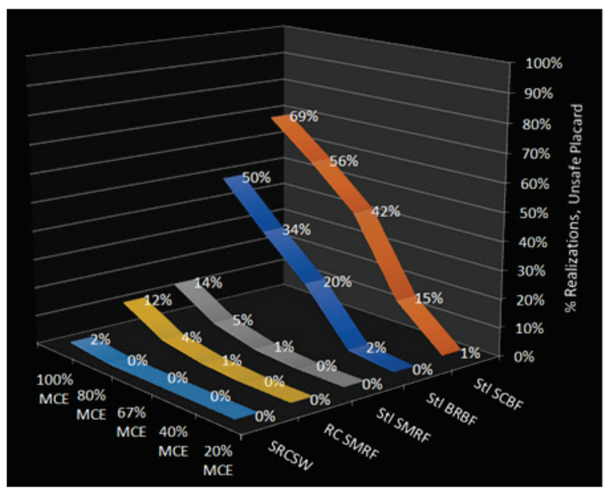
Risk Category II, Office



Risk Category II, Healthcare



Risk Category IV, Office



Risk Category IV, Healthcare

Figure 5-15 Comparison of median probabilities of incurring an unsafe placard for each system, separated by Risk Category and occupancy, average of representative designs.

The most severe damage states in nearly all structural fragility groups are associated with a potential loss of stability of the structure, triggering an unsafe placard. Although nonstructural damage can be an indicator of potential structural damage, most nonstructural fragility groups are not associated with an unsafe placard. Exceptions include exit stairs and exterior curtain wall window systems. Medical equipment fragilities used in this study do not include triggers for unsafe placards.

Overall, median probabilities of incurring an unsafe placard vary significantly between systems. In general, trends in relative losses between systems, and the change in losses with shaking intensity, are consistent across changes in occupancy and Risk Category.

Because medical equipment fragilities used in this study do not include triggers for unsafe placards, the presence of medical equipment in healthcare occupancies does not result in an increased potential for red tags, and the probability of incurring an unsafe placard for office and healthcare archetypes within the same Risk Category are nearly identical. Differences that can be observed between Risk Category II office and healthcare archetypes in Figure 5-15 are due to differences in the archetype design space (low-, mid-, and high-rise archetypes for office occupancies, versus only low- and mid-rise archetypes for healthcare occupancies).

Between risk categories, the probability of incurring an unsafe placard for Risk Category IV archetypes relative to Risk Category II archetypes is significantly lower for certain systems, and only somewhat lower for other systems. Steel SMRF, RC SMRF, and Special RCSW systems have a significantly lower probability of incurring an unsafe placard for Risk Category IV archetypes relative to Risk Category II archetypes. Steel SCBF and Steel BRBF systems, however, have a comparatively smaller change in the probability of incurring an unsafe placard because engineering practice is expected to result in designs that are significantly stiffer that required, and design story drifts have already been conservatively taken as less than code maximum drift limits (see Tables 2-5 and 2-6). As a result, these archetypes benefit less from more restrictive Risk Category IV drift criteria than other systems.

The following system-specific observations are made:

- Steel SMRF systems – Residual drift is a significant trigger for unsafe placards; unsafe placards are also triggered by damage to structural components at higher shaking intensities.
- RC SMRF systems – Residual drift is a significant trigger for unsafe placards; unsafe placards are also triggered by damage to structural components at higher shaking intensities.

- Steel BRBF systems – Residual drift is the primary trigger for unsafe placards.
- Steel SCBF systems – Brace damage, which initiates at low shaking intensities, is a significant trigger for unsafe placards and primary contributor to losses in both Risk Category II and Risk Category IV archetypes at all shaking intensities.
- Special RCSW systems – Damage to concrete shear walls is the primary trigger for unsafe placards, but probabilities of incurring an unsafe placard are comparatively low overall.

5.4.5 Repairability

Repairability 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.

Reparability is a measure of probability that the building will sustain damage that renders a building irreparable. This occurs when the total cost of repairing all damaged components and systems exceeds a threshold value, when the residual story drift ratio exceeds a level that is considered practicable to repair, or when collapse occurs. FEMA uses a threshold value of 50% when contemplating whether a damaged structure should be replaced or repaired and the 50% value is used in this study. If a structure is deemed unrepairable the repair time is set to a replacement time of 720 days.

Repairability is a positive metric, and higher values indicate better performance. A reparability of 100% indicates that in nearly every realization, the building was repairable. A reparability of 25% means the building was repairable in only one-quarter of the realizations, and in the other three-quarters of the realizations the building was deemed a total loss.

Median repairability by system is summarized in Table 5-16. Results are based on representative design points for each system, averaged across all hazard levels (Low SDC D, SDC D, and SDC E/F) and building heights (low-, mid-, and high-rise).

A comparison of median repairability for each system, separated by risk category and occupancy, is shown in Figure 5-16. Overall, median repairability varies somewhat between systems, and is generally high for most systems. Trends in relative repairability between systems, and the change in repairability with shaking intensity, are consistent across changes in occupancy and Risk Category.

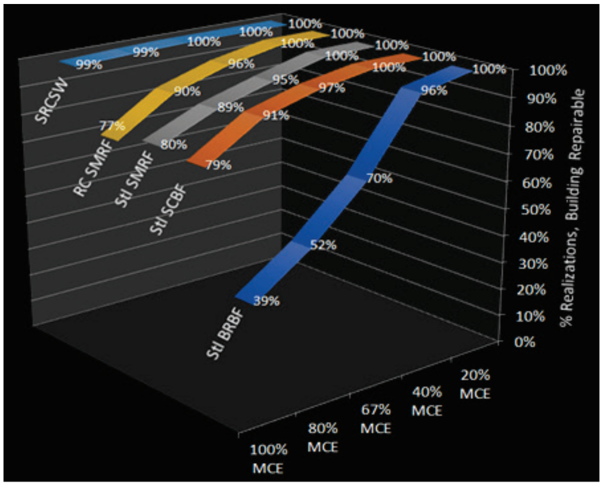
Table 5-16 Average Repairability for Representative Designs – Median Results

Seismic Force-Resisting System	Repairability				
	20%	40%	Design	80%	MCE
Risk Category II – Office					
Steel SMRF	100%	100%	95%	89%	80%
RC SMRF	100%	100%	96%	90%	77%
Steel BRBF	100%	96%	70%	52%	39%
Steel SCBF	100%	100%	97%	91%	79%
Special RCSW	100%	100%	100%	99%	99%
Risk Category II – Healthcare (Medical Office Building or Laboratory)					
Steel SMRF	100%	99%	89%	80%	68%
RC SMRF	99%	96%	91%	86%	82%
Steel BRBF	99%	93%	67%	49%	36%
Steel SCBF	98%	93%	85%	78%	68%
Special RCSW	99%	96%	91%	86%	82%
Risk Category IV – Office (Emergency Operations Center)					
Steel SMRF	100%	100%	99%	97%	91%
RC SMRF	100%	100%	100%	100%	100%
Steel BRBF	100%	96%	70%	52%	39%
Steel SCBF	100%	100%	97%	91%	79%
Special RCSW	100%	100%	100%	100%	100%
Risk Category IV – Healthcare (Hospital)					
Steel SMRF	100%	100%	99%	96%	91%
RC SMRF	100%	99%	98%	96%	94%
Steel BRBF	100%	97%	79%	65%	50%
Steel SCBF	100%	98%	96%	94%	90%
Special RCSW	100%	99%	98%	96%	94%

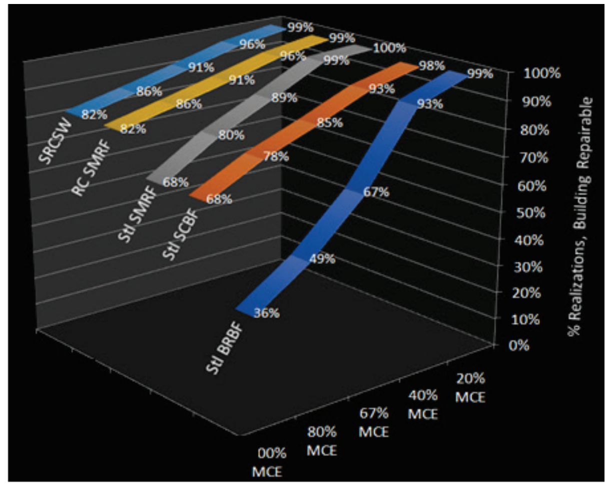
Within a given Risk Category, repairability for healthcare occupancies is somewhat lower than office occupancies. This is attributed to the presence of high-value medical equipment associated with healthcare occupancies. Between Risk Categories, repairability for Risk Category IV archetypes is higher than Risk Category II archetypes, especially at higher shaking intensities. The following observations are made:

- In Risk Category II office archetypes, repairability is driven almost entirely by residual drift and collapse.
- In Risk Category IV office archetypes, repairability is driven by residual drift.
- In Risk Category II and IV healthcare archetypes, damage to high-value medical equipment can drive repair costs over the 50% threshold

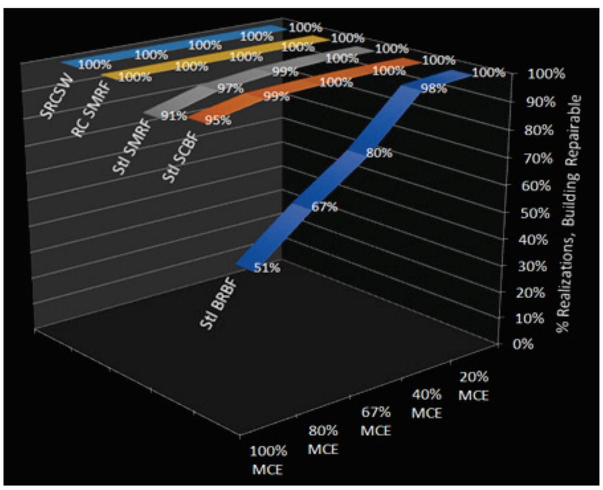
triggering loss of repairability. Risk Category IV design criteria improves repairability for healthcare occupancies, due to higher design forces for medical equipment.



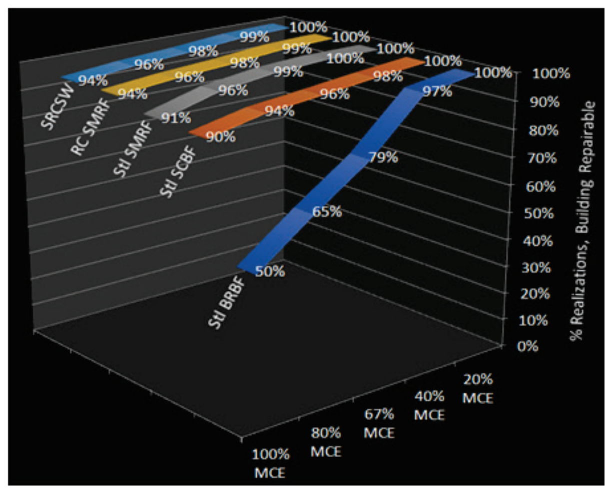
Risk Category II, Office



Risk Category II, Healthcare



Risk Category IV, Office



Risk Category IV, Healthcare

Figure 5-16 Comparison of median repairability for each system, separated by Risk Category and occupancy, average of representative designs.

5.5 Performance Assessment Results by Hazard Level

Archetypes in each system were designed and evaluated in three different hazard settings: Low SDC D, SDC D, and SDC E/F. Performance assessment results are reported for repair cost, casualty rate, and probability of unsafe placard for representative designs in each system, separated by hazard level and Risk Category, and summarized in the sections that follow. Because trends for repair time and repairability metrics are similar to trends observed for repair costs, repair time and repairability metrics have not been reported by hazard level.

5.5.1 Repair Cost by Hazard Level

Median repair costs at different hazard levels are summarized for Risk Category II archetypes in Table 5-17 and Risk Category IV archetypes in Table 5-18. Results are based on representative design points for each system, averaged across all building heights (low-, mid-, and high-rise), and occupancies (office and healthcare). Comparative plots are shown in Figure 5-17.

Overall, median repair costs vary significantly between systems. With the exception of Steel BRBF archetypes (discussed in more detail below), repair costs increase as the hazard level increases. The increase in design force with hazard level is not sufficient to maintain the same level of performance in higher hazard settings. Drift sensitive systems in Low SDC D remain susceptible to residual drift demands at design earthquake (67% MCE) and higher shaking intensities, even when ground accelerations are lower. General trends in relative losses between systems, and the change in losses with shaking intensity, are consistent across all hazard levels and risk categories.

Much of the change between hazard levels is attributed to nonstructural components and systems that are installed in accordance with prescriptive

Table 5-17 Average Repair Costs by Hazard Level, Representative Designs, Risk Category II – Median Results

Seismic Force-Resisting System	Hazard Level	Repair Cost (% of Replacement Value)				
		20% MCE	40% MCE	67% MCE	80% MCE	100% MCE
Steel SMRF	Low SCD D	0%	1%	6%	12%	17%
	SDC D	0%	2%	10%	17%	23%
	SDC E	0%	4%	13%	21%	36%
RC SMRF	Low SCD D	0%	1%	7%	13%	19%
	SDC D	0%	3%	11%	19%	45%
	SDC E	0%	4%	14%	25%	56%
Steel BRBF	Low SCD D	0%	5%	29%	70%	89%
	SDC D	1%	6%	24%	47%	73%
	SDC E	1%	8%	27%	54%	88%
Steel SCBF	Low SCD D	2%	9%	16%	21%	29%
	SDC D	3%	13%	23%	29%	41%
	SDC E	4%	17%	28%	33%	52%
Special RCSW	Low SCD D	0%	2%	7%	10%	12%
	SDC D	0%	4%	11%	16%	20%
	SDC E	0%	6%	15%	20%	24%

Table 5-18 Average Repair Costs by Hazard Level, Representative Designs, Risk Category IV – Median Results

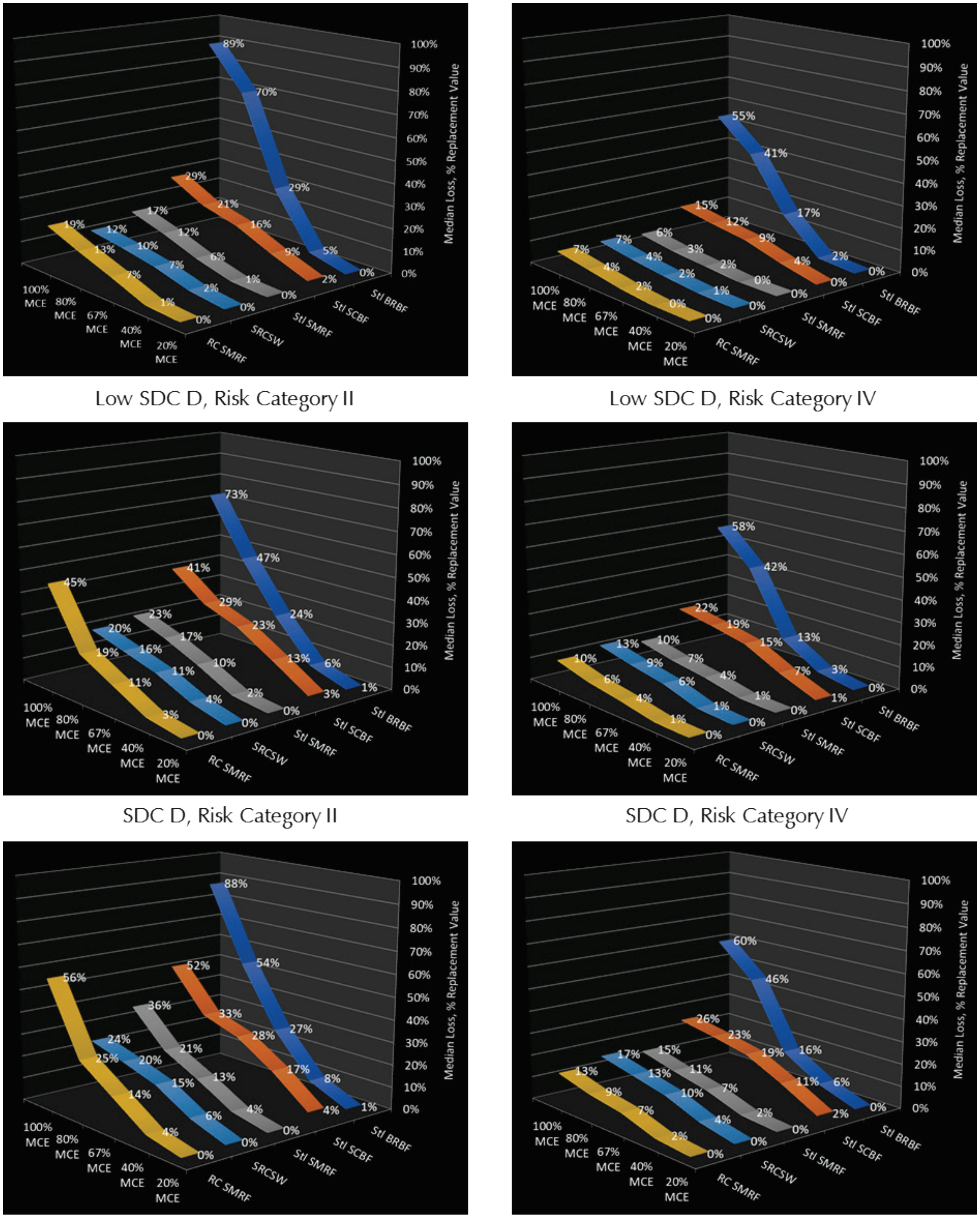
Seismic Force-Resisting System	Hazard Level	Repair Cost (% of Replacement Value)				
		20% MCE	40% MCE	67% MCE	80% MCE	100% MCE
Steel SMRF	Low SCD D	0%	0%	2%	3%	6%
	SDC D	0%	1%	4%	7%	10%
	SDC F	0%	2%	7%	11%	15%
RC SMRF	Low SCD D	0%	0%	2%	4%	7%
	SDC D	0%	1%	4%	6%	10%
	SDC F	0%	2%	7%	9%	13%
Steel BRBF	Low SCD D	0%	2%	17%	41%	55%
	SDC D	0%	3%	13%	42%	58%
	SDC F	0%	6%	16%	46%	60%
Steel SCBF	Low SCD D	0%	4%	9%	12%	15%
	SDC D	1%	7%	15%	19%	22%
	SDC F	2%	11%	19%	23%	26%
Special RCSW	Low SCD D	0%	1%	2%	4%	7%
	SDC D	0%	1%	6%	9%	13%
	SDC F	0%	4%	10%	13%	17%

standards (e.g., suspended ceiling systems), or are exempt from seismic design requirements (e.g., small diameter threaded-steel piping).

Losses to acceleration-controlled components are sensitive to changes in acceleration demand. For example, in Risk Category II archetypes, suspended lay-in acoustical tile ceiling systems of a given area are assigned to a single fragility that is applicable from Low SDC D (0.5g short-period spectral acceleration) to SDC E (1.33g short-period spectral acceleration). In lower hazard settings, demands are lower, and ceilings are less likely to be damaged. Conversely, in higher hazard settings, demands are higher, and ceilings are more likely to be damaged.

Small diameter threaded-steel piping is typically exempt from seismic bracing requirements, so the median capacity of piping system fragilities are the same across all hazard levels. As a result, losses due to interior flooding, which are controlled by small diameter threaded-steel piping, are significantly more likely to occur as the seismic hazard level increases.

Average repair costs for Risk Category IV archetypes are lower than Risk Category II archetypes across all hazard levels, and the relative performance of representative Risk Category IV archetypes followed patterns similar to those of Risk Category II archetypes.



Low SDC D, Risk Category II

Low SDC D, Risk Category IV

SDC D, Risk Category II

SDC D, Risk Category IV

SDC E, Risk Category II

SDC F, Risk Category IV

Figure 5-17 Comparison of median repair costs, separated by hazard level and Risk Category, average of representative designs.

In most systems, repair costs for Risk Category IV archetypes are reduced by about 50% relative to Risk Category II archetypes, at design earthquake (67% MCE) and higher shaking intensities. Significant reductions in repair costs in higher Risk Categories are observed across all systems at all hazard levels.

Steel BRBF systems exhibit a non-typical trend in the magnitude of losses at different hazard levels. In most systems, repair costs increase as the hazard level increases. In Steel BRBF systems, however, median repair costs are higher in Low SDC D, lower in SDC D, and then higher again in SDC E/F. This trend is observed in both Risk Category II and Risk Category IV archetypes. It is attributed to the sensitivity of Steel BRBF performance to residual drift, and changes in potential residual drift demands caused by differences in design strength and stiffness at each hazard level.

Design story drift limits are the same in Low SDC D, SDC D, and SDC E/F, but the resulting design strengths and stiffnesses change with changes in force level. As a result, Steel BRBF archetypes in Low SDC D have longer effective periods and lower yield strengths compared to archetypes in SDC D and SDC E/F. Steel BRBF archetypes in Low SDC D are more likely to experience higher drift demands, and increased likelihood of residual drift, causing higher repair costs, even in the lower hazard setting. In SDC D, the higher relative strength and stiffness reduce potential repair costs, even as the hazard increases. In SDC E/F, the change in strength and stiffness is not enough to overcome the increase in hazard level, so losses increase at the higher hazard level.

5.5.2 Casualty Rate by Hazard Level

Median casualty rates at different hazard levels are summarized for Risk Category II archetypes in Table 5-19 and Risk Category IV archetypes in Table 5-20. Results are based on representative design points for each system, averaged across all building heights (low-, mid-, and high-rise), and occupancies (office and healthcare). Comparative plots are shown in Figure 5-18.

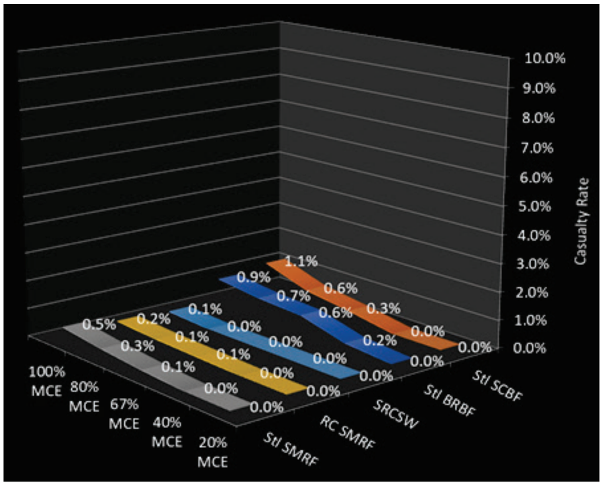
Overall, median casualty rates vary significantly between systems, and increase as the hazard level increases. The increase in design force with hazard level is not sufficient to maintain the same level of performance in higher hazard settings. General trends in relative losses between systems, and the change in losses with shaking intensity, are consistent across all hazard levels and risk categories. Much of the change between hazard levels is attributed to nonstructural components and systems. Ceilings systems and

Table 5-19 Average Casualty Rates by Hazard Level, Representative Designs, Risk Category II – Median Results

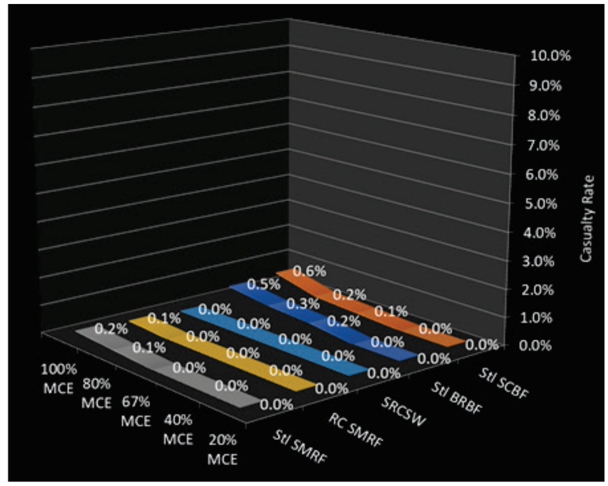
Seismic Force-Resisting System	Hazard Level	Casualty Rate				
		20% MCE	40% MCE	67% MCE	80% MCE	100% MCE
Steel SMRF	Low SCD D	0.0%	0.0%	0.1%	0.3%	0.5%
	SDC D	0.0%	0.0%	0.3%	0.5%	0.9%
	SDC E	0.0%	0.1%	0.5%	1.0%	1.7%
RC SMRF	Low SCD D	0.0%	0.0%	0.1%	0.1%	0.2%
	SDC D	0.0%	0.0%	0.1%	0.3%	0.8%
	SDC E	0.0%	0.0%	0.3%	0.8%	1.6%
Steel BRBF	Low SCD D	0.0%	0.2%	0.6%	0.7%	0.9%
	SDC D	0.0%	0.2%	0.9%	1.7%	2.7%
	SDC E	0.0%	0.4%	1.9%	3.2%	4.5%
Steel SCBF	Low SCD D	0.0%	0.0%	0.3%	0.6%	1.1%
	SDC D	0.0%	0.3%	2.0%	3.4%	4.8%
	SDC E	0.1%	1.1%	4.1%	5.8%	7.1%
Special RCSW	Low SCD D	0.0%	0.0%	0.0%	0.0%	0.1%
	SDC D	0.0%	0.0%	0.3%	0.7%	1.4%
	SDC E	0.0%	0.1%	1.0%	1.9%	3.3%

Table 5-20 Average Casualty Rates by Hazard Level, Representative Designs, Risk Category IV – Median Results

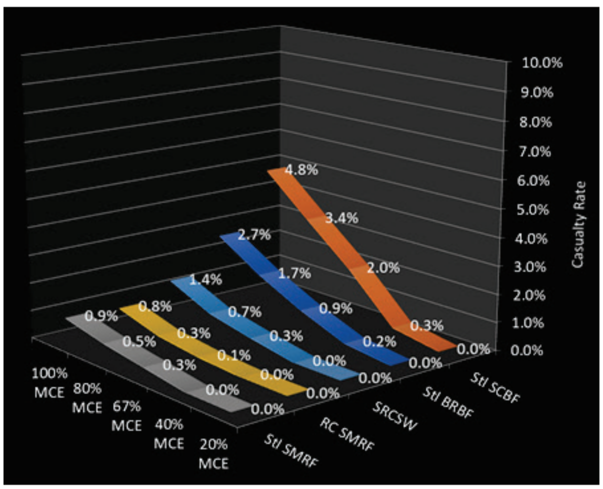
Seismic Force-Resisting System	Hazard Level	Casualty Rate				
		20% MCE	40% MCE	67% MCE	80% MCE	100% MCE
Steel SMRF	Low SCD D	0.0%	0.0%	0.0%	0.1%	0.2%
	SDC D	0.0%	0.0%	0.1%	0.2%	0.5%
	SDC F	0.0%	0.0%	0.2%	0.5%	1.2%
RC SMRF	Low SCD D	0.0%	0.0%	0.0%	0.0%	0.1%
	SDC D	0.0%	0.0%	0.0%	0.1%	0.3%
	SDC F	0.0%	0.0%	0.1%	0.3%	0.9%
Steel BRBF	Low SCD D	0.0%	0.0%	0.2%	0.3%	0.5%
	SDC D	0.0%	0.1%	0.4%	0.9%	1.8%
	SDC F	0.0%	0.2%	1.1%	2.1%	3.6%
Steel SCBF	Low SCD D	0.0%	0.0%	0.1%	0.2%	0.6%
	SDC D	0.0%	0.2%	1.3%	2.5%	4.2%
	SDC F	0.0%	0.7%	3.4%	5.2%	6.8%
Special RCSW	Low SCD D	0.0%	0.0%	0.0%	0.0%	0.0%
	SDC D	0.0%	0.0%	0.2%	0.4%	0.9%
	SDC F	0.0%	0.0%	0.6%	1.3%	2.4%



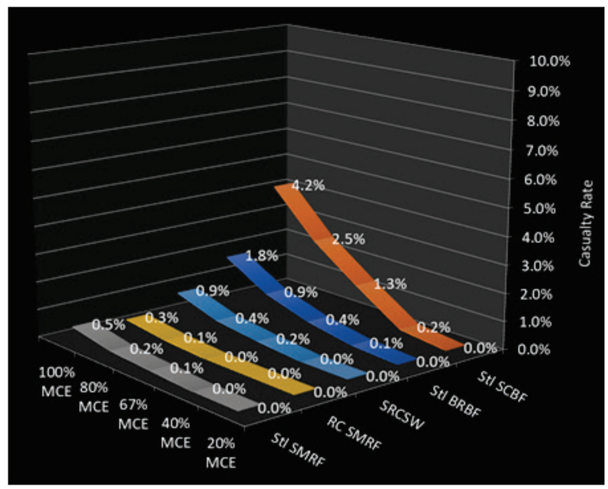
Low SDC D, Risk Category II



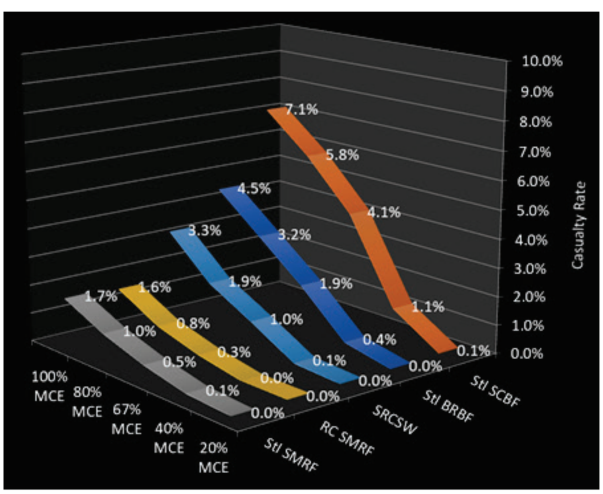
Low SDC D, Risk Category IV



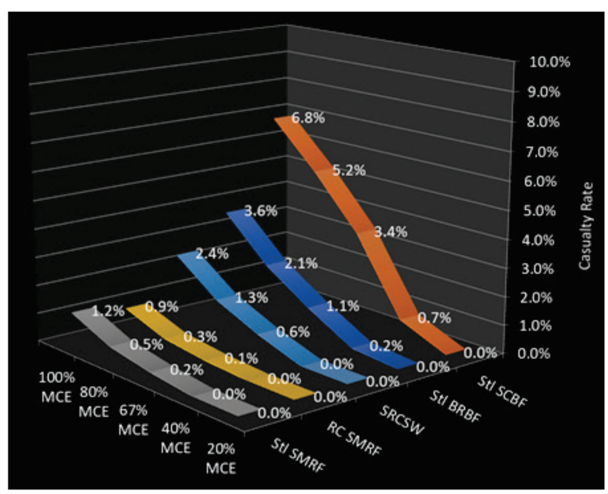
SDC D, Risk Category II



SDC D, Risk Category IV



SDC E, Risk Category II



SDC F, Risk Category IV

Figure 5-18 Comparison of median casualty rates separated by hazard level and Risk Category, average of representative designs.

exterior window systems are identified as significant contributors to casualties caused by nonstructural components.

The relative performance of Risk Category IV archetypes follow patterns similar to those of Risk Category II archetypes, but median casualty rates for Risk Category IV archetypes are only slightly lower than Risk Category II archetypes across all hazard levels. Although Risk Category IV structures benefit from more stringent design requirements relative to Risk Category II structures, higher lateral strengths and stiffnesses result in higher floor accelerations, which reduce the relative benefit associated with changes in nonstructural design criteria. Also, because suspended lay-in acoustical tile ceiling systems are a significant contributor to casualties, and improvement in the lateral capacity of Risk Category IV ceiling systems relative to Risk Category II ceiling systems is modest, improvement in casualty rates for Risk Category IV structures is limited.

For a given system at a given point in the design space, design story drift ratios are the same in all hazard settings. As a result, casualties due to exterior window systems do not vary significantly between hazard levels.

Strength-controlled systems (e.g., Steel SCBF, Steel BRBF, and Special RCSW systems) have comparatively higher casualty rates due to higher floor accelerations. Because of damage to acceleration-controlled components such as ceiling systems, strength-controlled systems benefit less from Risk Category IV design requirements.

Drift-controlled systems (e.g., Steel SMRF and RC SMRF systems) have comparatively lower casualty rates. Because of reduced damage to drift-controlled components such as exterior window systems, drift-controlled systems benefit comparatively more from Risk Category IV design requirements.

5.5.3 Probability of Unsafe Placard by Hazard Level

Median probabilities of incurring an unsafe placard at different hazard levels are summarized for Risk Category II archetypes in Table 5-21 and Risk Category IV archetypes in Table 5-22. Results are based on representative design points for each system, averaged across all building heights (low-, mid-, and high-rise), and occupancies (office and healthcare). Comparative plots are shown in Figure 5-19.

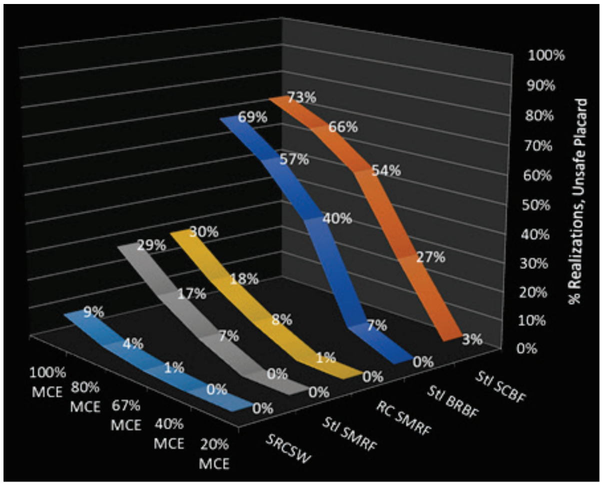
Overall, median probabilities of incurring an unsafe placard vary significantly between systems. With the exception of Risk Category II Steel BRBF archetypes (discussed below), the probability of incurring an unsafe

Table 5-21 Average Probabilities of Incurring an Unsafe Placard by Hazard Level, Representative Designs, Risk Category II – Median Results

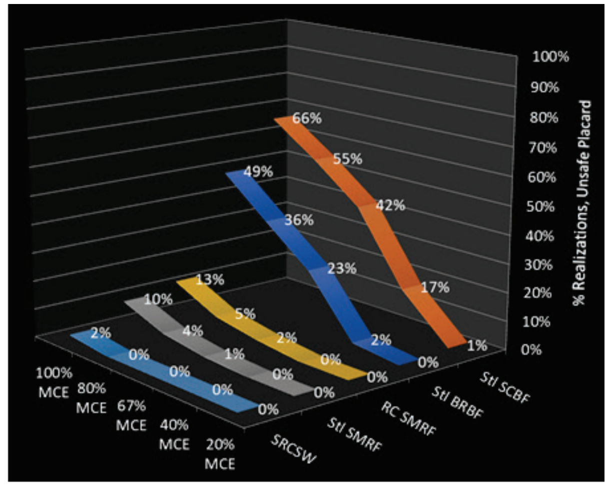
Seismic Force-Resisting System	Hazard Level	Probability of Unsafe Placard				
		MCE	40% MCE	67% MCE	80% MCE	100% MCE
Steel SMRF	Low SCD D	0%	0%	7%	17%	29%
	SDC D	0%	1%	10%	20%	33%
	SDC E	0%	1%	12%	24%	38%
RC SMRF	Low SCD D	0%	1%	8%	18%	30%
	SDC D	0%	2%	14%	26%	42%
	SDC E	0%	2%	17%	32%	49%
Steel BRBF	Low SCD D	0%	7%	40%	57%	69%
	SDC D	0%	5%	28%	47%	60%
	SDC E	0%	4%	30%	50%	64%
Steel SCBF	Low SCD D	3%	27%	54%	66%	73%
	SDC D	4%	30%	59%	72%	82%
	SDC E	4%	29%	59%	74%	83%
Special RCSW	Low SCD D	0%	0%	1%	4%	9%
	SDC D	0%	0%	2%	4%	12%
	SDC E	0%	0%	2%	5%	13%

Table 5-22 Average Probabilities of Incurring an Unsafe Placard by Hazard Level, Representative Designs, Risk Category IV – Median Results

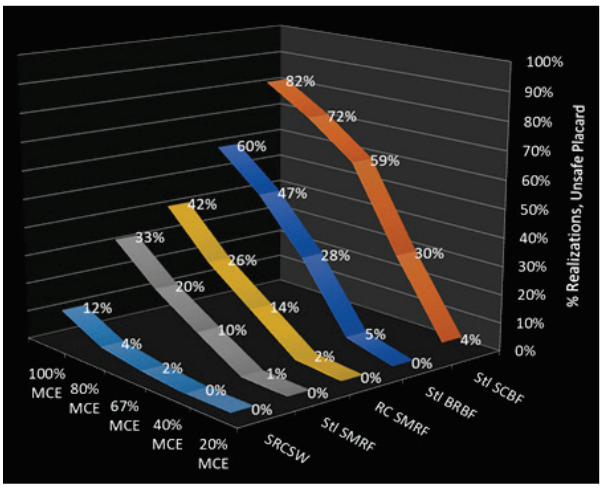
Seismic Force-Resisting System	Hazard Level	Probability of Unsafe Placard				
		MCE	40% MCE	67% MCE	80% MCE	100% MCE
Steel SMRF	Low SCD D	0%	0%	1%	4%	10%
	SDC D	0%	0%	2%	6%	15%
	SDC F	0%	0%	2%	7%	18%
RC SMRF	Low SCD D	0%	0%	2%	5%	13%
	SDC D	0%	0%	1%	4%	12%
	SDC F	0%	0%	1%	3%	11%
Steel BRBF	Low SCD D	0%	2%	23%	36%	49%
	SDC D	0%	2%	20%	34%	50%
	SDC F	0%	2%	19%	34%	51%
Steel SCBF	Low SCD D	1%	17%	42%	55%	66%
	SDC D	1%	15%	42%	57%	69%
	SDC F	1%	14%	43%	60%	72%
Special RCSW	Low SCD D	0%	0%	0%	0%	2%
	SDC D	0%	0%	0%	1%	2%
	SDC F	0%	0%	0%	0%	3%



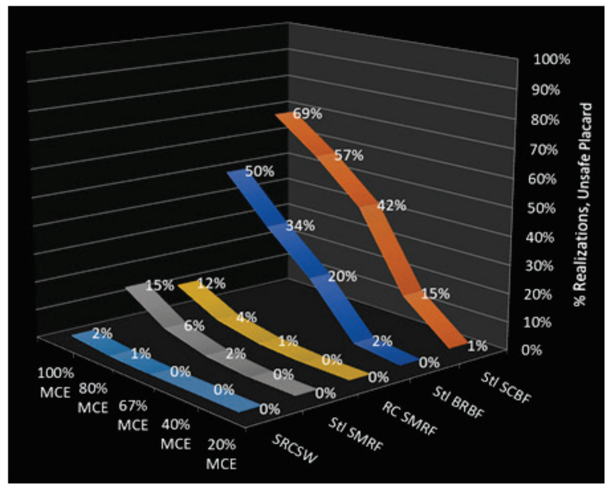
Low SDC D, Risk Category II



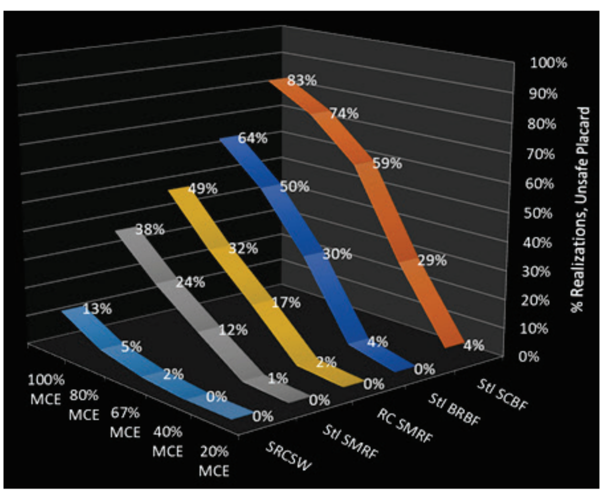
Low SDC D, Risk Category IV



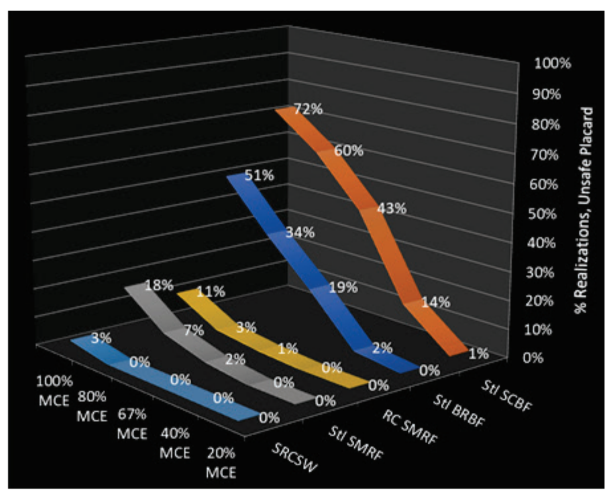
SDC D, Risk Category II



SDC D, Risk Category IV



SDC E, Risk Category II



SDC F, Risk Category IV

Figure 5-19 Comparison of median probabilities of incurring an unsafe placard, separated by hazard level and Risk Category, average of representative designs.

placard increases as the hazard level increases. Although changes between hazard levels are relatively small, the increase in design force with hazard level is not sufficient to maintain the same level of performance in higher hazard settings. General trends in relative losses between systems, and the change in losses with shaking intensity, are consistent across all hazard levels and risk categories.

Average probabilities of incurring an unsafe placard for Risk Category IV archetypes are lower than Risk Category II archetypes across all hazard levels, and the relative performance of representative Risk Category IV archetypes follow patterns similar to those of Risk Category II archetypes. Brace damage in Steel SCBF systems, which initiates at low shaking intensities, is a significant trigger for unsafe placards and a primary contributor to losses in both Risk Category II and Risk Category IV archetypes across all hazard levels.

As observed in the case of repair costs, Steel BRBF systems exhibit a non-typical trend in the probability of incurring an unsafe placard with changes in hazard level. Median probabilities of incurring an unsafe placard are higher in Low SDC D, lower in SDC D, and then higher again in SDC E/F. This trend is observed in Risk Category II archetypes, but not in Risk Category IV archetypes, and is attributed to changes in the likelihood of residual drift due to differences in design strength and stiffness, as described in Section 5.5.1. As a result, Steel BRBF archetypes in Low SDC D are more likely to experience higher drift demands and increased likelihood of residual drift relative to SDC D archetypes, even in the lower hazard setting. In SDC E/F, the change in strength and stiffness is not enough to overcome the increase in hazard level, so probabilities of incurring an unsafe placard increase at the higher hazard level.

5.6 Performance Assessment Results by Building Height

In each system, archetypes were designed and evaluated for three different height variants: low-rise (2-story and 3-story), mid-rise (5-story), and high-rise (12-story). The break between low-rise and mid-rise archetypes was selected to align with requirements in ASCE/SEI 7-10 Table 12.12-1, which permit larger story drifts for structures that are four stories or less in height. To represent high-rise buildings, 12-story archetypes were selected to be within the upper limit of 15 stories for buildings analyzed using the simplified analysis procedure in FEMA P-58, Volume 1.

Not all height variants were designed and evaluated in all Risk Categories or occupancies. To match typical construction practices, Risk Category IV office occupancies considered only low-rise and mid-rise archetypes. Similarly, healthcare occupancies considered only low-rise and mid-rise archetypes in both Risk Categories II and IV.

Performance assessment results in terms of repair costs are reported by building height and summarized below for representative designs in office and healthcare occupancies. Trends for other performance metrics are similar to trends observed for repair costs and are not explicitly reported by building height.

5.6.1 Repair Cost by Height, Office Occupancies

Median repair costs for low-, mid-, and high-rise office occupancies are summarized for Risk Category II archetypes in Table 5-23 and Risk Category IV archetypes in Table 5-24. Results are based on representative design points for each system, averaged across all hazard levels (Low SDC D, SDC D, and SDC E/F). Comparative plots are shown in Figure 5-20.

Overall, median repair costs vary significantly by building height and Risk Category. Trends observed among the variations in height and Risk Category are attributed most significantly to changes in design story drift ratio.

Table 5-23 Average Repair Costs by Building Height, Representative Designs, Risk Category II, Office Occupancies – Median Results

Seismic Force-Resisting System	Building Height	Repair Cost (% of Replacement Value)				
		20% MCE	40% MCE	67% MCE	80% MCE	100% MCE
Steel SMRF	Low-Rise	0%	1%	7%	14%	29%
	Mid-Rise	0%	1%	7%	13%	17%
	High-Rise	0%	1%	3%	5%	6%
RC SMRF	Low-Rise	0%	2%	11%	20%	66%
	Mid-Rise	0%	1%	5%	12%	19%
	High-Rise	0%	0%	2%	4%	6%
Steel BRBF	Low-Rise	0%	5%	18%	74%	100%
	Mid-Rise	0%	2%	10%	27%	65%
	High-Rise	0%	3%	29%	50%	75%
Steel SCBF	Low-Rise	1%	9%	18%	22%	31%
	Mid-Rise	1%	8%	16%	20%	24%
	High-Rise	4%	10%	16%	21%	49%
Special RCSW	Low-Rise	0%	1%	5%	7%	10%
	Mid-Rise	0%	1%	4%	6%	8%
	High-Rise	0%	1%	3%	5%	7%

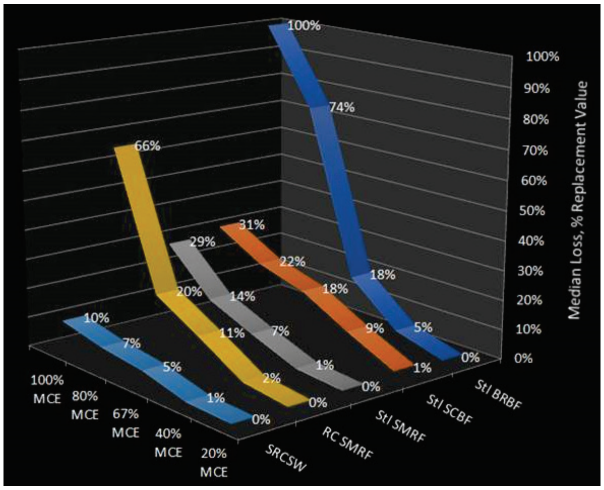
Table 5-24 Average Repair Costs by Building Height, Representative Designs, Risk Category IV, Office Occupancies – Median Results

Seismic Force-Resisting System	Building Height	Repair Cost (% of Replacement Value)				
		20% MCE	40% MCE	67% MCE	80% MCE	100% MCE
Steel SMRF	Low-Rise	0%	0%	3%	6%	9%
	Mid-Rise	0%	0%	2%	4%	6%
RC SMRF	Low-Rise	0%	0%	3%	5%	9%
	Mid-Rise	0%	0%	2%	4%	5%
Steel BRBF	Low-Rise	0%	3%	12%	72%	100%
	Mid-Rise	0%	2%	5%	8%	11%
Steel SCBF	Low-Rise	0%	6%	12%	15%	18%
	Mid-Rise	1%	6%	12%	14%	16%
Special RCSW	Low-Rise	0%	1%	4%	6%	8%
	Mid-Rise	0%	1%	3%	5%	7%

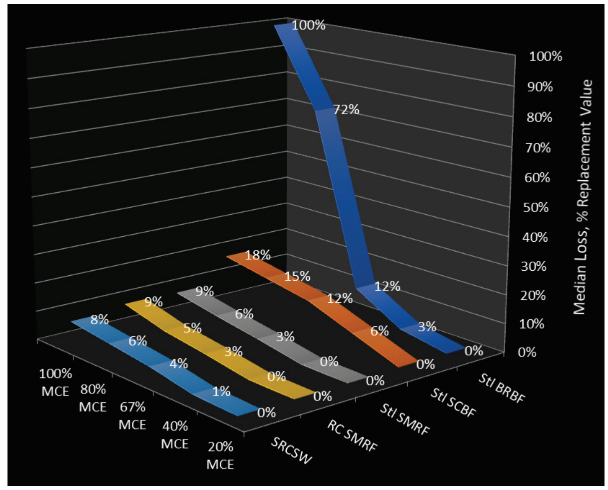
In general, low-rise, Risk Category II, office archetypes exhibited the highest repair costs across all systems. This is attributed to larger design story drift ratios permitted for low-rise structures in ASCE/SEI 7-10, resulting in a greater likelihood of residual drift in stronger shaking intensities, especially in drift-controlled systems (e.g., Steel SMRF and RC SMRF) and drift-sensitive systems (e.g., Steel BRBF). Low-rise strength-controlled systems (e.g., Steel SCBF and Special RCSW) experienced higher floor accelerations and increased losses due to interior flooding, even in lower shaking intensities.

Mid-rise, Risk Category II, office archetypes benefit from lower design story drift ratios relative to low-rise archetypes, which reduces the potential for residual drift in drift-controlled and drift-sensitive systems, and reduces nonstructural damage to partitions and exterior window systems. Mid-rise archetypes also have longer effective periods relative to low-rise archetypes, which reduces floor accelerations and reduces damage to acceleration-controlled mechanical, electrical, and plumbing equipment and ceiling systems.

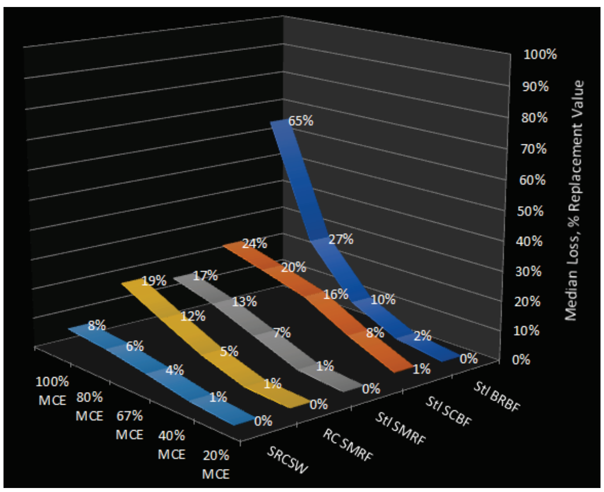
High-rise, Risk Category II, office archetypes are designed for code-maximum allowable drift ratios, which are smaller than design drift ratios for low-rise buildings, but larger than design drift ratios assumed for most mid-rise archetypes. As a result, repair costs for drift-sensitive high-rise archetypes (e.g., Steel BRBF and Steel SCBF) are lower than repair costs for low-rise archetypes, but higher than repair costs for mid-rise archetypes. High rise moment frame and shear wall archetypes exhibit the lowest repair costs across all building heights.



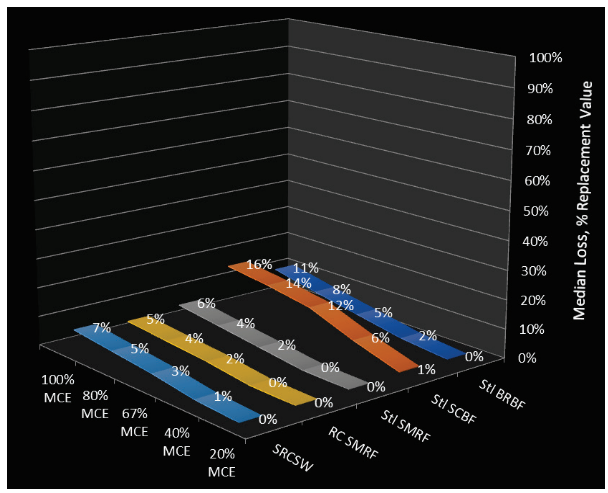
Low-Rise, Risk Category II, Office



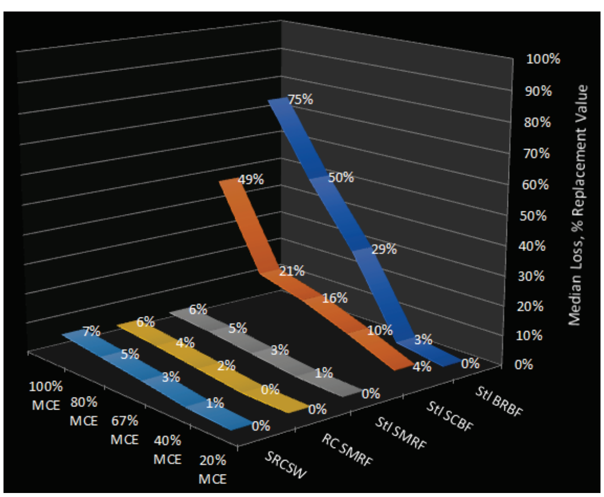
Low-Rise, Risk Category IV, Office



Mid-Rise, Risk Category II, Office



Mid-Rise, Risk Category IV, Office



High-Rise, Risk Category II, Office

Figure 5-20 Comparison of median repair costs for office occupancies, separated by building height and Risk Category, average of representative designs.

Risk Category IV structures are designed for higher lateral forces and lower story drift ratios than Risk Category II structures. In drift-controlled systems, this reduces the potential for residual drift and reduces the overall magnitude of repair costs. In some strength-controlled systems, increases in design base shear result in a corresponding increase in stiffness, and have a similar effect. In general, median repair costs for Risk Category IV office archetypes are reduced relative to Risk Category II archetypes, although reductions are most significant at design earthquake (67% MCE) and higher shaking intensities.

In Steel BRBF systems, it is possible to increase design strength without increasing stiffness. Because Steel BRBF archetypes are designed for story drift ratios that are already less than code maximum allowable drift ratios, low-rise Steel BRBF archetypes benefit less from more stringent Risk Category IV drift limits, and repair costs in low-rise, Risk Category IV, Steel BRBF archetypes are essentially unchanged from low-rise, Risk Category II archetypes.

Design story drift ratios for mid-rise Steel BRBF archetypes are smaller than low-rise archetypes, and change with Risk Category. In the case of mid-rise Steel BRBF archetypes, repair costs for Risk Category IV archetypes are substantially reduced relative to Risk Category II archetypes.

Median repair costs for Special RCSW archetypes are low relative to other systems across all building heights and Risk Categories.

5.6.2 Repair Cost by Height, Healthcare Occupancies

Median repair costs for low-rise and mid-rise healthcare occupancies are summarized for Risk Category II archetypes in Table 5-25 and Risk Category IV archetypes in Table 5-26. Results are based on representative design points for each system, averaged across all hazard levels (Low SDC D, SDC D, and SDC E/F). Comparative plots are shown in Figure 5-21.

Overall, median repair costs vary significantly by building height and Risk Category. As observed for office occupancies, trends among the variations in height and Risk Category for healthcare occupancies are attributed most significantly to changes in design story drift ratio.

In general, low-rise, Risk Category II, healthcare archetypes exhibit the highest repair costs, attributed to larger design story drift ratios permitted for low-rise structures in ASCE/SEI 7-10, resulting in a greater likelihood of residual drift. Mid-rise, Risk Category II, healthcare archetypes benefit from lower design story drift ratios relative to low-rise archetypes, which reduce the potential for residual drift in drift-controlled and drift-sensitive systems, and reduce the potential for nonstructural damage to partitions and exterior window systems.

Table 5-25 Average Repair Costs by Building Height, Representative Designs, Risk Category II, Healthcare Occupancies – Median Results

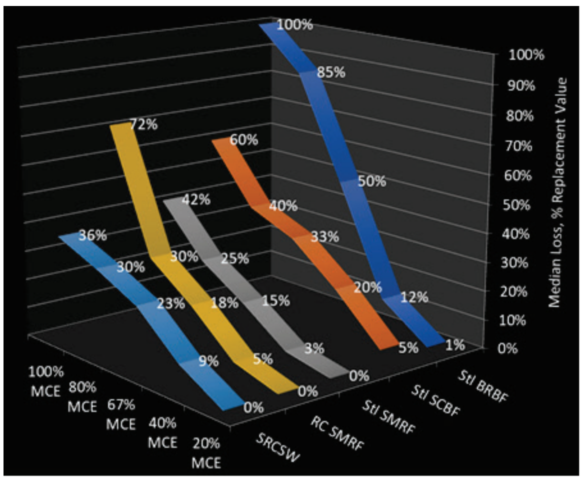
Seismic Force-Resisting System	Building Height	Repair Cost (% of Replacement Value)				
		20% MCE	40% MCE	67% MCE	80% MCE	100% MCE
Steel SMRF	Low-Rise	0%	3%	15%	25%	42%
	Mid-Rise	0%	2%	11%	18%	24%
RC SMRF	Low-Rise	0%	5%	18%	30%	72%
	Mid-Rise	0%	2%	10%	19%	27%
Steel BRBF	Low-Rise	1%	12%	50%	85%	100%
	Mid-Rise	0%	6%	18%	39%	73%
Steel SCBF	Low-Rise	5%	20%	33%	40%	60%
	Mid-Rise	2%	13%	22%	27%	31%
Special RCSW	Low-Rise	0%	9%	23%	30%	36%
	Mid-Rise	0%	4%	12%	16%	21%

Table 5-26 Average Repair Costs by Building Height, Representative Designs, Risk Category IV, Healthcare Occupancies – Median Results

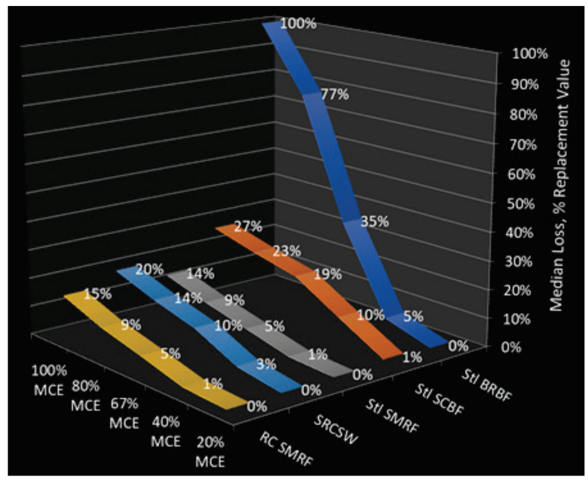
Seismic Force-Resisting System	Building Height	Repair Cost (% of Replacement Value)				
		20% MCE	40% MCE	67% MCE	80% MCE	100% MCE
Steel SMRF	Low-Rise	0%	1%	5%	9%	14%
	Mid-Rise	0%	1%	4%	7%	10%
RC SMRF	Low-Rise	0%	1%	5%	9%	15%
	Mid-Rise	0%	1%	4%	6%	10%
Steel BRBF	Low-Rise	0%	5%	35%	77%	100%
	Mid-Rise	0%	3%	8%	12%	17%
Steel SCBF	Low-Rise	1%	10%	19%	23%	27%
	Mid-Rise	1%	6%	13%	16%	19%
Special RCSW	Low-Rise	0%	3%	10%	14%	20%
	Mid-Rise	0%	1%	6%	9%	12%

In general, median repair costs for Risk Category IV healthcare archetypes are significantly lower than Risk Category II archetypes, which is attributed to the higher design forces and lower design story drift ratios associated with more stringent Risk Category IV design criteria. In the case of low-rise Steel BRBF systems, however, this trend is far less pronounced. Because low-rise Steel BRBF archetypes are designed for story drift ratios that are already less than code maximum allowable drift ratios, low-rise Steel BRBF archetypes benefit less from more stringent Risk Category IV drift limits, and repair costs in low-rise, Risk Category IV, Steel BRBF archetypes change very little from low-rise, Risk Category II archetypes.

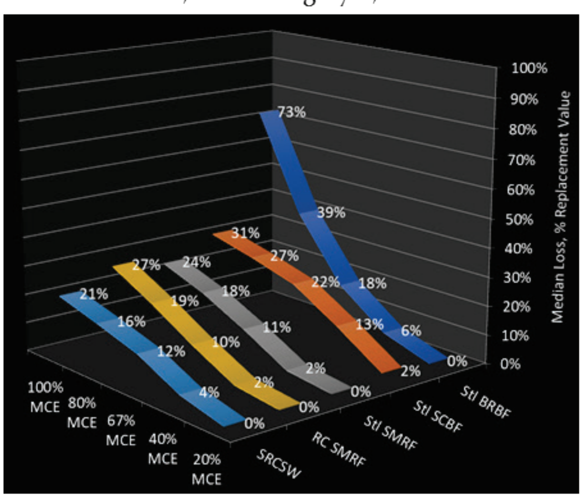
Design story drift ratios for mid-rise Steel BRBF archetypes are smaller than low-rise archetypes, and change with Risk Category. In the case of mid-rise Steel BRBF archetypes, repair costs for Risk Category IV archetypes are substantially reduced relative to Risk Category II archetypes.



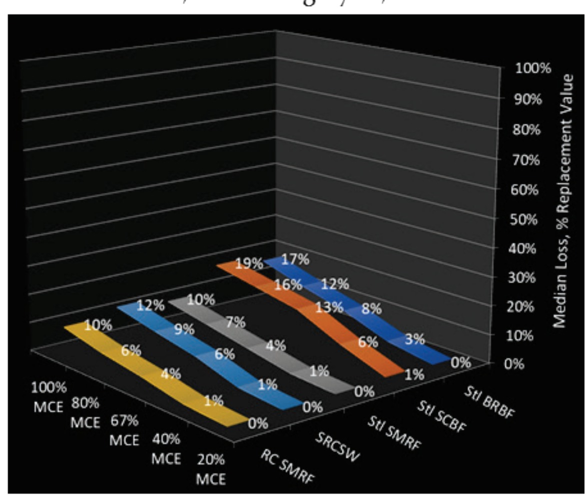
Low-Rise, Risk Category II, Healthcare



Low-Rise, Risk Category IV, Healthcare



Mid-Rise, Risk Category II, Healthcare



Mid-Rise, Risk Category IV, Healthcare

Figure 5-21 Comparison of median repair costs for healthcare occupancies, separated by building height and Risk Category, average of representative designs.

The relative contribution of medical equipment to total repair costs is important in healthcare occupancies. Medical equipment is grouped in three categories: (1) mobile components, such as anesthesia units, ultrasound units, surgical tables, and patient beds; (2) imaging systems, such as CT scanners, MRI machines, and X-ray systems; and (3) other fixed medical equipment, such as operating lights, sterilizers, and laminar flow hoods.

Like other nonstructural components, medical equipment in mid-rise, Risk Category II, healthcare archetypes benefit from longer effective periods and lower floor accelerations relative to low-rise archetypes. For example, at design earthquake shaking (67% MCE), damage to medical equipment in low-rise, Risk Category II, healthcare archetypes contributes approximately 55% to total median repair costs, on average, across all systems. In mid-rise, Risk Category II, healthcare archetypes, the contribution of damage to medical equipment reduces to approximately 45% of total median repair costs, on average, across all systems.

In absolute terms, medical equipment contributions to median repair costs are substantially lower in Risk Category IV healthcare archetypes compared to Risk Category II healthcare archetypes, but structural repair costs are also lower. At design earthquake shaking (67% MCE), damage to medical equipment in low-rise, Risk Category IV, healthcare archetypes contributes approximately 65% to total median repair costs, on average, across all systems. In mid-rise, Risk Category IV, healthcare archetypes, the contribution of damage to medical equipment reduces to approximately 37% of total median repair costs, on average, across all systems.

Chapter 6
Summary, Recommendations, and Generalized Performance of Buildings

This report describes the application of the FEMA P-58 assessment methodology to a group of archetypical buildings representative of structures conforming to the seismic design requirements of the current building code. It is intended 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.

This chapter provides a summary of the work, extracts general observations on system performance, presents a framework for generalized performance expectations for code-conforming buildings, and provides recommendations for establishing seismic performance objectives and improving the seismic performance of buildings based on findings from this study.

6.1 Summary of Approach and Limitations

Performance of code-conforming buildings is not uniquely defined. Building codes establish minimum criteria that must be followed, but structural engineers have latitude in applying design requirements, and can make design decisions that significantly influence the performance of buildings in earthquakes.

To quantify the performance capability of code-conforming buildings, 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. Seismic requirements, however, only specify the minimum strength and maximum allowable drift boundaries of the design space. Assumptions for upper-bound strength and lower-bound drift limits were used to complete the design space.

Because of the large number of archetypes considered, a simplified design and analysis approach was used to determine structural properties associated with each archetype, and to estimate structural response quantities (drifts, accelerations, and velocities) for performance assessment. Structural demands were calculated using the simplified analysis procedure in FEMA P-58, Volume 1. Quantities of nonstructural components and systems were developed using the *Normative Quantity Estimation Tool* in FEMA P-58, Volume 3.

Assessments were performed using the *Performance Assessment Calculation Tool* (PACT) version 3.03. All performance assessment results can be viewed in the *Performance Estimation Tool* (PET), provided in FEMA P-58, Volume 3. Results and conclusions are subject to the following limitations:

- Performance is characterized in a probabilistic manner, with explicit recognition of the uncertainties involved in assessing building performance. Results are based on probability distributions and are inherently uncertain.
- Performance metrics are reported at the median confidence level. Median values provide the expected performance in the middle of the distribution, with half of the possible values higher, and half of the possible values lower than the reported value.
- Assessment results are applicable to buildings that fully comply with all structural and nonstructural seismic design requirements in ASCE/SEI 7-10, and all strength and detailing requirements in referenced material

design standards. Available information is limited to the systems studied, which does not include wood light-frame construction.

- Life safety performance, as measured by an acceptably low probability of collapse, is achieved by designing and constructing buildings in accordance with the requirements in ASCE/SEI 7-10.
- Foundation elements, components deemed rugged, and building contents (such as furniture and electronic equipment not designated as medical equipment) were excluded from building performance models, and could be subject to damage that has not been considered in this study.
- Healthcare occupancy performance models include judgement-based fragilities for medical equipment developed specifically for this study. The resulting performance estimates for healthcare occupancies should be considered lower-bound, and used for comparative purposes only

6.2 Summary Observations on Performance

FEMA P-58 assessment of code-conforming buildings shows 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. Although traditional code performance expectations focus on safety, current design requirements are shown to provide some measure of protection of property.

Factors affecting performance in terms of FEMA P-58 performance metrics include:

- seismic force-resisting system selection;
- design strength and lateral stiffness;
- robustness of structural member design and connection detailing;
- nonstructural design criteria and quality of installation;
- occupancy and Risk Category; and
- seismic hazard level and Seismic Design Category.

6.2.1 Observations on System-Specific Performance

System-specific results of FEMA P-58 performance assessments are reported in Chapter 5. Results are presented by system, occupancy, performance metric, hazard level, and building height. The following general observations are made:

- Overall, losses increase, and reparability decreases, as the intensity of shaking increases from 20% MCE to 100% MCE.

- Losses are lower, and repairability is higher, for Risk Category IV archetypes relative to Risk Category II archetypes, in both office and healthcare occupancies.
- Within a given Risk Category, losses for healthcare occupancies are higher than office occupancies because of the presence of high-value medical equipment and increased (24-hour) occupancy associated with healthcare occupancies.
- Residual drift is a major contributor to losses at shaking intensities of 67% MCE and higher.
- Risk Category IV archetypes benefit from more stringent design story drift criteria, with substantially reduced structural damage and potential for residual drift.
- More stringent design requirements in Risk Category IV reduce, but do not eliminate, damage to nonstructural components. Interior flooding still contributes significantly to losses in Risk Category IV archetypes because demands increase, but the capacity of the piping system responsible for interior flooding is not influenced by Risk Category.
- Prescriptive requirements for suspended lay-in acoustical tile ceiling systems are the same in Low SDC D, SDC D, and SDC E/F. In higher hazard settings, ceilings are more likely to be damaged because demands increase, but the capacity is not influenced by hazard level.
- Overall, losses increase as the hazard level increases from Low SDC D, to SDC D, and SDC E/F. The increase in design force with hazard level is not sufficient to maintain the same level of performance in higher hazard settings.
- In general, low-rise archetypes exhibit the highest losses (as compared to mid-rise and high-rise archetypes) across all systems. This is attributed to larger design story drift ratios permitted for low-rise structures in ASCE/SEI 7-10, resulting in a greater likelihood of residual drift in stronger shaking intensities, especially in drift-controlled systems (e.g., Steel SMRF and RC SMRF) and drift-sensitive systems (e.g., Steel BRBF).
- Low-rise strength-controlled systems (e.g., Steel SCBF and Special RCSW) experience higher floor accelerations and increases in losses due to interior flooding, even in lower shaking intensities.
- Although system-specific performance is shown to be highly variable, all seismic force-resisting systems can be designed to meet required (or

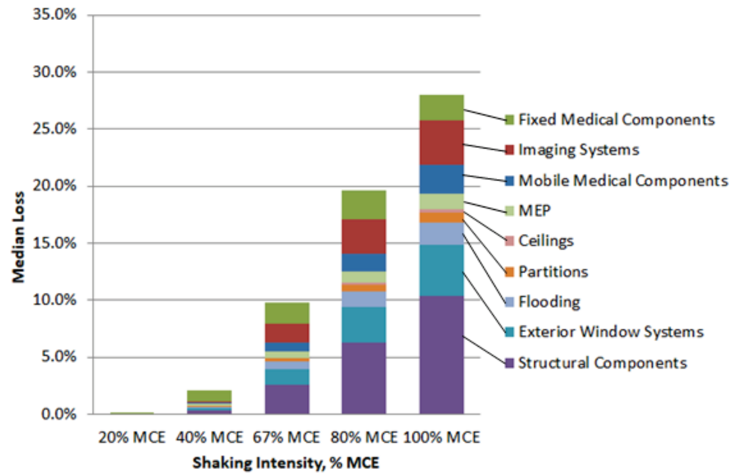
desired) performance objectives through the judicious selection of design story drift ratio and minimum lateral strength.

6.2.2 Structural and Nonstructural Contributions to Performance

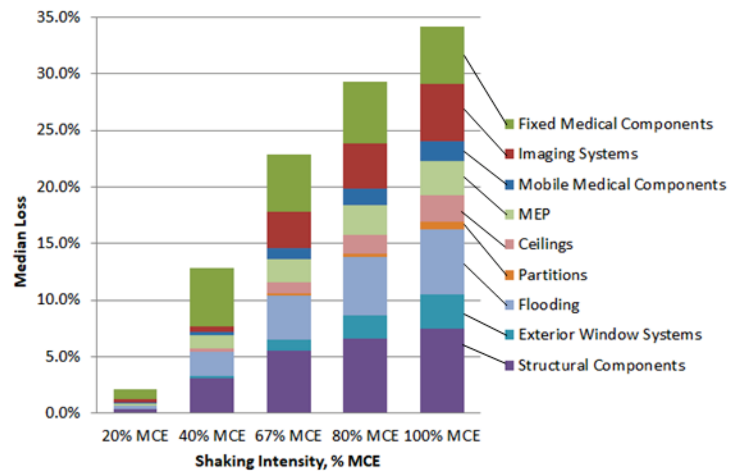
Components contributing most significantly to losses in each system are discussed and tabulated in Chapter 5. The relative contribution of each structural and nonstructural component to total loss is a function of the acceleration- or drift-controlled response of the structural system and the sensitivity of the component to acceleration-, velocity-, or drift-controlled damage.

Figure 6-1 illustrates the approximate relative contributions between structural, nonstructural, and medical components, for one building height (mid-rise), and the change in relative contributions between a typical drift-controlled system (RC SMRF), a typical strength-controlled system (Steel SCBF), and Risk Category II and Risk Category IV design criteria. The figure also shows the change in relative contributions as the intensity of shaking increases. Although the figure is based on information from a specific example, the overall trends in losses are general. In Figure 6-1, the following general observations can be made:

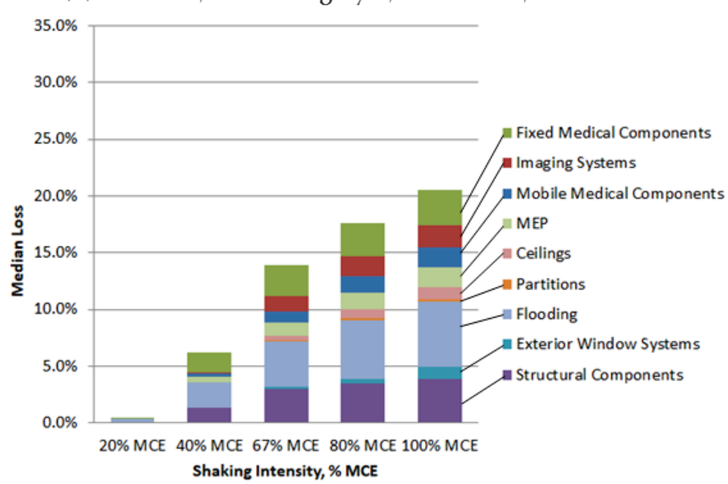
- Losses in acceleration-controlled nonstructural components (e.g., fixed medical equipment, imaging systems, ceilings, and piping contributing to flooding) are proportionally lower in flexible, drift-controlled structural systems, such as moment frames.
- Losses in drift-controlled components (e.g., partitions and exterior window systems) and velocity-controlled components (e.g., mobile medical equipment) are proportionally lower in stiff, strength-controlled systems, such as concentrically braced frames.
- Losses in Risk Category IV buildings are proportionally lower than Risk Category II buildings overall, due to increases in design lateral forces, decreases in design story drift ratios, and enhanced detailing requirements associated with more stringent Risk Category IV design criteria.
- Reductions in design story drift ratio associated with Risk Category IV design criteria can significantly reduce losses in drift-controlled nonstructural components.
- Increases in strength and stiffness associated with Risk Category IV design criteria can increase losses in acceleration-controlled nonstructural components.



(a) Mid-Rise, Risk Category II, RC SMRF, Healthcare



(b) Mid-Rise, Risk Category II, Steel SCBF, Healthcare



(c) Mid-Rise, Risk Category IV, Steel SCBF, Healthcare

Figure 6-1 Comparison of relative contributions to median repair costs for mid-rise, Risk Category II and IV, RC SMRF and Steel SCBF, healthcare occupancies.

- At lower shaking intensities, structural losses contribute proportionately less, and nonstructural losses contribute proportionally more, to total losses. As the intensity of shaking increases, the relative contribution due to structural losses increases.

6.3 Generalized Performance Expectations for Code-Conforming Buildings

Although the assessed performance of code-conforming buildings shows that performance varies significantly across the range of code-complying systems, the code does not specify different performance objectives for different systems. For this reason, the results of FEMA P-58 performance assessments, across all systems, were generalized into a single overarching statement of the performance expectation for all code-conforming systems.

Generalized performance expectations were developed based on a combination of: (1) performance assessment results averaged across the design space for each system; (2) experience in post-earthquake damage investigations and subsequent repairs; and (3) engineering judgement. The resulting generalized performance expectations for code-conforming buildings are provided in Table 6-1.

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. Table 6-1 provides the expected performance for Risk Category II and Risk Category IV, office and healthcare occupancies, using FEMA P-58 performance metrics, taken as median values of the following measures:

- **Repair Cost.** The cost to restore damaged components to their pre-earthquake condition, expressed as a percentage of the replacement value of the building. Repair costs represent only a single aspect of the 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 the repairs, and the cost of financing the repairs.
- **Repair Time.** The number of days required to restore damaged components to their pre-earthquake condition, which is only a portion of the time to return a building to its pre-earthquake conditions. Additional time is required to identify, plan, and permit the work, arrange financing, and hire and mobilize the contractors.

Table 6-1 Generalized Performance Expectations for Code-Conforming Buildings

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%

- **Casualty Rate.** Casualties include loss of life or serious injury requiring hospitalization. Casualty rate is the probability of any one occupant in a building becoming a casualty as a result of an earthquake.
- **Probability of Unsafe Placard.** The probability that a building will be posted unsafe to occupy following an earthquake, based on the occurrence of structural or nonstructural damage that is considered significant enough to trigger an unsafe posting.
- **Repairability.** 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.

6.4 Considerations for Establishing Seismic Performance Objectives

Building codes have historically provided minimum requirements for protection of public safety and welfare. The stated performance expectations for seismic design requirements, however, have been continually evolving over recent code cycles, trending towards more explicit statements of expected performance and development of more specific performance-based design criteria. Although the stated intent of seismic design requirements has included concepts of performance, functionality, and repair costs for some time, these statements are largely qualitative or aspirational, lacking specific quantitative methods for measuring the intended performance.

FEMA P-58 performance metrics provide a quantitative definition of performance that extends beyond the basic safety intent of the building code, and the FEMA P-58 methodology provides a quantitative procedure for measuring performance expectations. The following sections provide recommendations that should be considered in establishing future seismic performance objectives based on FEMA P-58 performance metrics.

6.4.1 Determine Acceptable Performance

Performance assessment results presented herein provide a measure of what current code requirements provide in terms of repair cost, repair time, casualty rates, unsafe placarding, and repairability. Further study, and interaction with additional stakeholders, including the public, is necessary to determine if the measured performance matches societal expectations, and would be considered acceptable.

6.4.2 Determine Appropriate Performance Targets

Code-based performance objectives could be aspirational (i.e., targeting an ideal level of performance) or practical (i.e., targeting the performance that is currently being achieved). If the performance that is being achieved does not match expectations, or is not considered acceptable, then higher performance objectives may need to be considered.

6.4.3 Consider Necessary Levels of Confidence

Generalized performance expectations for code-conforming buildings have been developed based on median results. Median results are 50^{th} percentile values, providing 50% confidence that performance targets will not be exceeded. In some circumstances, such as in establishing code-based performance objectives, higher confidence levels (e.g., 90^{th} percentile values) may be appropriate, providing a higher level of confidence that performance targets will not be exceeded. Further study on the cost associated with higher design criteria and the benefits of improved seismic performance are needed to evaluate the necessary level of confidence.

6.4.4 Consider the Relative Performance of Systems

It is implicitly expected that seismic design requirements result in consistent performance across all systems. This is generally true in terms of collapse safety, but relative performance of systems in terms of FEMA P-58 performance metrics is highly variable. Consideration should be given as to whether the least common denominator will be used to establish performance targets, or if design requirements for lower-performing systems will be tuned to match the performance of higher-performing systems. Establishing system equivalency will be a politically charged debate between different material interests.

6.4.5 Define Functional Performance

Codes and standards have long targeted improved performance for higher occupancy and essential buildings. Recent update cycles have included aspirational structural and nonstructural reliability criteria attempting to define what is needed to achieve higher performance. With the ongoing attention on resilience concepts, and continual evolution of codes to include more explicit performance-based design concepts, the development of functional performance criteria is needed.

FEMA P-58 performance metrics, at an appropriate hazard level, could be used to quantitatively define functional performance. A frequent earthquake, which is intended to capture an earthquake that may reasonably be expected to occur once in the life a building, could be considered for measuring functional performance. One possible definition for such an earthquake is ground shaking having a 50% probability of exceedance in 50 years. However, with the current risk-based formulation for seismic hazard, the intensity for such an earthquake would vary significantly by location, as would the resulting performance. Further study is needed to define reasonable criteria at an appropriate hazard level.

6.5 Recommendations for Improving the Seismic Performance of Buildings

Based on the results of FEMA P-58 performance assessments performed in this study, certain design requirements were shown to have a significant impact on performance. The following adjustments to seismic design requirements could be considered to improve the resulting seismic performance of code-conforming buildings:

- Larger design story drift ratios are permitted for buildings less than four stories in height. Buildings designed to higher drift limits are prone to increased structural damage and a higher likelihood of residual drift. Low-rise buildings in this study exhibited disproportionately larger losses than mid-rise and high-rise buildings. Permissible drift limits for low-rise buildings should be reconsidered.
- Interior flooding due to pipe failure is a significant source of losses and extended repair times frequently observed in past earthquakes. Buildings in this study also exhibited significant losses attributed to interior flooding. Although it may not be practical to seismically brace every small-bore piping system in a building, requiring the use of higher ductility piping in systems that will remain unbraced could substantially reduce losses to due to interior flooding.
- Suspended lay-in acoustical tile ceiling systems are a significant source of losses and casualty risk. Prescriptive seismic installation requirements for these systems are identical across SDC D, SDC E, and SDC F. Installation requirements for ceiling systems should be further developed to provide better protection in regions of very high seismicity.
- Proper construction of structural components, and proper installation of seismic bracing and anchorage of nonstructural components, are key to achieving the performance intended by seismic design requirements. Buildings constructed without adequate enforcement or construction quality assurance are likely to experience poor seismic performance. Continued efforts are needed to ensure that seismic codes and standards are properly applied and enforced in all regions of high seismic risk.

Appendix A

Structural Properties of Representative Archetypes

Structural properties of representative SDC D archetypes are summarized in Chapter 3, Section 3.8. Tables A-1 through A-10 in this appendix summarize key structural properties for representative low SDC D and SDC E/F archetypes in each system.

Table A-1 Range of Structural Properties for Representative Design Points, Steel SMRF Archetypes, Low SDC D

Height	Risk Category	Periods			Drift Ratios		Strengths	
		Bare-Frame Period, $T_{1,BF}$	Effective Period, $T_{1,EFF}$	Upper Limit Period, T_{max}	Design Story Drift Ratio	Yield Drift Ratio (%)	Minimum Base Shear Coefficient, C_s	Inferred Collapse Capacity, g
Low-Rise	II	2.06 - 2.39	1.75 - 2.03	0.73	0.021 - 0.025	1.0	0.06	2.1 - 3.6
	IV	1.37 - 1.49	1.17 - 1.27	0.73	0.014 - 0.015	1.0	0.09	3.2 - 5.4
Mid-Rise	II	2.49 - 2.84	2.11 - 2.41	1.11	0.018 - 0.02	1.0	0.04	1.4 - 2.4
	IV	1.32 - 1.49	1.12 - 1.27	1.11	0.009 - 0.01	1.0	0.06	2.1 - 3.6
High-Rise	II	5.15 - 5.92	4.41 - 5.04	2.23	0.018 - 0.02	1.0	0.02	0.8 - 1.2
	IV	-	-	-	-	-	-	-

Table A-2 Range of Structural Properties for Representative Design Points, Steel SMRF Archetypes, SDC E/F

Height	Risk Category	Periods			Drift Ratios		Strengths	
		Bare-Frame Period, $T_{1,BF}$	Effective Period, $T_{1,EFF}$	Upper Limit Period, T_{max}	Design Story Drift Ratio	Yield Drift Ratio (%)	Minimum Base Shear Coefficient, C_s	Inferred Collapse Capacity, g
Low-Rise	II	1.01 - 1.18	0.86 - 1.00	0.73	0.021 - 0.025	1.0	0.13	4.6 - 7.7
	IV	0.67 - 0.73	0.57 - 0.62	0.73	0.014 - 0.015	1.0	0.23 - 0.25	8.9 - 14.9
Mid-Rise	II	1.23 - 1.40	1.05 - 1.19	1.11	0.018 - 0.02	1.0	0.08 - 0.09	3.2 - 5.4
	IV	0.64 - 0.73	0.55 - 0.62	1.11	0.009 - 0.01	1.0	0.23 - 0.25	9.0 - 15.0
High-Rise	II	2.21 - 2.36	1.88 - 2.01	2.23	0.018 - 0.02	1.0	0.05 - 0.05	1.8 - 3.0
	IV	-	-	-	-	-	-	-

Table A-3 Range of Structural Properties for Representative Design Points, RC SMRF Archetypes, Low SDC D

Height	Risk Category	Periods: Bare-Frame Period, $T_{1,BF}$	Periods: Effective Period, $T_{1,EFF}$	Periods: Upper Limit Period, T_{max}	Drift Ratios: Design Story Drift Ratio	Drift Ratios: Yield Drift Ratio (%)	Strengths: Minimum Base Shear Coefficient, C_s	Strengths: Inferred Collapse Capacity, g
Low-Rise	II	2.06 - 2.39	1.13 - 1.31	0.61	0.021 - 0.025	0.55	0.06	2.0 - 2.6
	IV	1.37 - 1.49	0.76 - 0.82	0.61	0.014 - 0.015	0.55	0.09	3.0 - 3.9
Mid-Rise	II	2.49 - 2.84	1.37 - 1.56	0.96	0.018 - 0.02	0.55	0.05	1.5 - 1.9
	IV	1.32 - 1.49	0.72 - 0.82	0.96	0.009 - 0.01	0.55	0.08 - 0.09	2.9 - 3.8
High-Rise	II	5.18 - 5.92	2.85 - 3.26	2.11	0.018 - 0.02	0.55	0.02	0.7 - 0.9
	IV	-	-	-	-	-	-	-

Table A-4 Range of Structural Properties for Representative Design Points, RC SMRF Archetypes, SDC E/F

Height	Risk Category	Periods: Bare-Frame Period, $T_{1,BF}$	Periods: Effective Period, $T_{1,EFF}$	Periods: Upper Limit Period, T_{max}	Drift Ratios: Design Story Drift Ratio	Drift Ratios: Yield Drift Ratio (%)	Strengths: Minimum Base Shear Coefficient, C_s	Strengths: Inferred Collapse Capacity, g
Low-Rise	II	1.01 - 1.18	0.56 - 0.65	0.61	0.021 - 0.025	0.55	0.15 - 0.17	5.3 - 7.0
	IV	0.67 - 0.73	0.37 - 0.40	0.61	0.014 - 0.015	0.55	0.25	8.0 - 10.5
Mid-Rise	II	1.23 - 1.40	0.68 - 0.77	0.96	0.018 - 0.02	0.55	0.12 - 0.14	4.4 - 5.8
	IV	0.64 - 0.73	0.35 - 0.40	0.96	0.009 - 0.01	0.55	0.25	8.0 - 10.5
High-Rise	II	2.21 - 2.36	1.22 - 1.30	2.11	0.018 - 0.02	0.55	0.07 - 0.08	2.5 - 3.2
	IV	-	-	-	-	-	-	-

Table A-5 Range of Structural Properties for Representative Design Points, Steel BRBF Archetypes, Low SDC D

Height	Risk Category	Periods: Bare-Frame Period, $T_{1,BF}$	Periods: Effective Period, $T_{1,EFF}$	Periods: Upper Limit Period, T_{max}	Drift Ratios: Design Story Drift Ratio	Drift Ratios: Yield Drift Ratio (%)	Strengths: Minimum Base Shear Coefficient, C_s	Strengths: Inferred Collapse Capacity, g
Low-Rise	II	1.04 - 1.29	0.89 - 1.10	0.48	0.01 - 0.0125	0.3	0.06	2.0 - 2.6
	IV	1.04 - 1.29	0.89 - 1.10	0.48	0.01 - 0.0125	0.3	0.09	3.0 - 3.9
Mid-Rise	II	1.63 - 2.00	1.38 - 1.70	0.96	0.01 - 0.0125	0.3	0.05	1.6 - 1.9
	IV	1.25 - 1.44	1.06 - 1.22	0.96	0.008 - 0.009	0.3	0.07	2.2 - 2.9
High-Rise	II	3.89 - 5.05	3.30 - 4.29	1.85	0.013 - 0.016	0.3	0.02	0.8 - 1.0
	IV	-	-	-	-	-	-	-

Table A-6 Range of Structural Properties for Representative Design Points, Steel BRBF Archetypes, SDC E/F

Height	Risk Category	Periods			Drift Ratios		Strengths	
		Bare-Frame Period, $T_{1,BF}$	Effective Period, $T_{1,EFF}$	Upper Limit Period, T_{max}	Design Story Drift Ratio	Yield Drift Ratio (%)	Minimum Base Shear Coefficient, C_s	Inferred Collapse Capacity, g
Low-Rise	II	0.53 - 0.62	0.45 - 0.53	0.48	0.01 - 0.0125	0.3	0.17	5.3 - 7.0
	IV	0.53 - 0.62	0.45 - 0.53	0.48	0.01 - 0.0125	0.3	0.25	8.0 - 10.5
Mid-Rise	II	0.80 - 0.98	0.68 - 0.84	0.96	0.01 - 0.0125	0.3	0.11 - 0.14	3.6 - 5.0
	IV	0.61 - 0.70	0.52 - 0.60	0.96	0.008 - 0.009	0.3	0.24 - 0.25	7.5 - 9.0
High-Rise	II	1.88 - 2.19	1.60 - 1.88	1.85	0.013 - 0.016	0.3	0.05 - 0.06	1.6 - 2.1
	IV	-	-	-	-	-	-	-

Table A-7 Range of Structural Properties for Representative Design Points, Steel SCBF Archetypes, Low SDC D

Height	Risk Category	Periods			Drift Ratios		Strengths	
		Bare-Frame Period, $T_{1,BF}$	Effective Period, $T_{1,EFF}$	Upper Limit Period, T_{max}	Design Story Drift Ratio	Yield Drift Ratio (%)	Minimum Base Shear Coefficient, C_s	Inferred Collapse Capacity, g
Low-Rise	II	0.53 - 0.79	0.45 - 0.67	0.32	0.005 - 0.01	0.35	0.08	2.0
	IV	0.50 - 0.67	0.42 - 0.57	0.32	0.004 - 0.008	0.35	0.13	3.0
Mid-Rise	II	0.66 - 1.21	0.56 - 1.03	0.64	0.005 - 0.01	0.35	0.08	2.0
	IV	0.62 - 1.00	0.53 - 0.85	0.64	0.004 - 0.008	0.35	0.13	3.0
High-Rise	II	1.96 - 3.52	1.66 - 2.99	1.24	0.009 - 0.016	0.35	0.05	1.1
	IV	-	-	-	-	-	-	-

Table A-8 Range of Structural Properties for Representative Design Points, Steel SCBF Archetypes, SDC E/F

Height	Risk Category	Periods			Drift Ratios		Strengths	
		Bare-Frame Period, $T_{1,BF}$	Effective Period, $T_{1,EFF}$	Upper Limit Period, T_{max}	Design Story Drift Ratio	Yield Drift Ratio (%)	Minimum Base Shear Coefficient, C_s	Inferred Collapse Capacity, g
Low-Rise	II	0.32 - 0.46	0.28 - 0.39	0.32	0.005 - 0.01	0.35	0.22	5.3
	IV	0.30 - 0.41	0.26 - 0.35	0.32	0.004 - 0.008	0.35	0.33	8.0
Mid-Rise	II	0.41 - 0.59	0.35 - 0.50	0.64	0.005 - 0.01	0.35	0.22	5.3
	IV	0.38 - 0.52	0.33 - 0.44	0.64	0.004 - 0.008	0.35	0.33	8.0
High-Rise	II	0.98 - 1.72	0.84 - 1.47	1.24	0.009 - 0.016	0.35	0.10 - 0.15	2.4 - 3.6
	IV	-	-	-	-	-	-	-

Table A-9 Range of Structural Properties for Representative Design Points, Special RCSW Archetypes, Low SDC D

Height	Risk Category	Periods: Bare-Frame Period, $T_{1,BF}$	Periods: Effective Period, $T_{1,EFF}$	Periods: Upper Limit Period, T_{max}	Drift Ratios: Design Story Drift Ratio	Drift Ratios: Yield Drift Ratio (%)	Strengths: Minimum Base Shear Coefficient, C_s	Strengths: Inferred Collapse Capacity, g
Low-Rise	II	0.30 - 0.47	0.27 - 0.42	0.32	0.003 - 0.006	0.5	0.10	2.3 - 3.8
	IV	0.30 - 0.47	0.27 - 0.42	0.32	0.003 - 0.006	0.5	0.15	3.4 - 5.6
Mid-Rise	II	0.42 - 0.65	0.37 - 0.59	0.64	0.003 - 0.006	0.26	0.10	2.3 - 3.8
	IV	0.42 - 0.65	0.37 - 0.59	0.64	0.003 - 0.006	0.26	0.15	3.4 - 5.6
High-Rise	II	1.66 - 2.29	1.50 - 2.06	1.24	0.009 - 0.013	0.63	0.06	1.3 - 2.1
	IV	-	-	-	-	-	-	-

Table A-10 Range of Structural Properties for Representative Design Points, Special RCSW Archetypes, SDC E/F

Height	Risk Category	Periods: Bare-Frame Period, $T_{1,BF}$	Periods: Effective Period, $T_{1,EFF}$	Periods: Upper Limit Period, T_{max}	Drift Ratios: Design Story Drift Ratio	Drift Ratios: Yield Drift Ratio (%)	Strengths: Minimum Base Shear Coefficient, C_s	Strengths: Inferred Collapse Capacity, g
Low-Rise	II	0.18 - 0.29	0.16 - 0.26	0.32	0.003 - 0.006	0.5	0.27	6.0 - 10.0
	IV	0.18 - 0.29	0.16 - 0.26	0.32	0.003 - 0.006	0.5	0.40	9.0 - 15.0
Mid-Rise	II	0.25 - 0.40	0.23 - 0.36	0.64	0.003 - 0.006	0.26	0.27	6.0 - 10.0
	IV	0.25 - 0.40	0.26 - 0.36	0.64	0.003 - 0.006	0.26	0.40	9.0 - 15
High-Rise	II	0.83 - 1.15	0.75 - 1.04	1.24	0.009 - 0.013	0.63	0.14 - 0.20	4.3 - 7.5
	IV	-	-	-	-	-	-	-

A.1 Variation in Structural Properties by Hazard Level

At all three hazard levels, archetypes conform to design and detailing requirements for Seismic Design Category D buildings. Between hazard levels, designs vary based on changes in the minimum required base shear due to differences in design spectra and the resulting spectral response acceleration parameters S_{DS} and S_{D1}.

Based on the simplified design process described in Chapter 3, design story drift ratios are determined by the point of interest in the design space, and the resulting stiffness, period, and base shear are back-calculated using code-based strength and period equations. As a result, design story drift ratios are the same at each hazard level, but the required design forces change with hazard, and the resulting periods (i.e., stiffnesses) must change accordingly to match the specified drift ratios at different force levels.

At the low SDC D hazard level, spectral response acceleration parameters are lower, than SDC D parameters. The resulting base shear strengths of representative low SDC D archetypes are lower, the effective stiffnesses are lower, and the resulting periods are longer relative to values for SDC D archetypes.

Similarly, at the SDC E/F hazard level, spectral response acceleration parameters are higher, the required base shear strengths are higher, the effective stiffnesses are higher, and the resulting periods are shorter relative to values for SDC D archetypes. Relative differences between hazard levels can be observed for each system by comparing values in the tables above with values provided in Chapter 3, Section 3.8.

Appendix B
Representative Nonstructural Performance Groups and Fragilities

This appendix summarizes the types, quantities, and performance groupings of nonstructural component and medical equipment fragilities used in this study. The types and quantities of nonstructural components assumed to be present in office and healthcare occupancies were based on information from the *Normative Quantity Estimation Tool* in FEMA P-58, Volume 3, supplemented with additional information described in Chapter 4 and below.

B.1 Office Occupancies

Office occupancies include offices and emergency operations centers assumed to have 100 percent office occupancy on every floor level, plus mechanical equipment on the roof. Performance groups and nonstructural component fragilities for typical floors of representative Risk Category II, mid-rise, office archetypes are provided in Tables B-1 through B-3. Performance groups and fragilities for typical rooftop mechanical equipment are provided in Table B-4. Fragility ID numbers and descriptions are taken from the PACT fragility database.

Table B-1 Representative Nonstructural Fragilities, Typical Floor, Direction 1, Mid-Rise Office Occupancies, Risk Category II

ID	Group	Description	Normative Quantity
B2022.035a	Exterior Curtain Wall	Midrise stick-built curtain wall, Config: Monolithic, Lamination: Not laminated, Glass Type: Annealed, Details: 1/4 in. (6 mm) AN monolithic; glass-frame clearance = 0.43 in. (11 mm); aspect ratio = 2:1 sealant = dry, 1 unit = 30 SF	86.67
C1011.001b	Fixed Partitions	Wall Partition, Type: Gypsum with metal studs, Partial Height, Fixed Below, Lateral Braced Above, 1 unit = 100 lineal feet	6.53
C1011.001c	Fixed Partitions	Wall Partition, Type: Gypsum with metal studs, Full Height, Fixed Below, Slip Track Above with returns, 1 unit = 100 lineal feet	1.63
C2011.001i	Stairs	Prefabricated steel with steel treads and landings with seismic joints that accommodate drift. Design Drift = D_{pI} = $D_p \times (I_e)$, 1 unit = one individual stair per floor.	1
C3011.001b	Wall Finishes	Wall Partition, Type: Gypsum + Wallpaper, Partial Height, Fixed Below, Lateral Braced Above, 1 unit = 100 lineal feet	0.53

Table B-2 Representative Nonstructural Fragilities, Typical Floor, Direction 2, Mid-Rise Office Occupancies, Risk Category II

ID	Group	Description	Normative Quantity
B2022.035a	Exterior Curtain Wall	Midrise stick-built curtain wall, Config: Monolithic, Lamination: Not laminated, Glass Type: Annealed, Details: 1/4 in. (6 mm) AN monolithic; glass-frame clearance = 0.43 in. (11 mm); aspect ratio = 2:1 sealant = dry, 1 unit = 30 SF	121.33
C1011.001b	Fixed Partitions	Wall Partition, Type: Gypsum with metal studs, Partial Height, Fixed Below, Lateral Braced Above, 1 unit = 100 lineal feet	4.67
C1011.001c	Fixed Partitions	Wall Partition, Type: Gypsum with metal studs, Full Height, Fixed Below, Slip Track Above with returns, 1 unit = 100 lineal feet	1.17
C2011.001i	Stairs	Prefabricated steel with steel treads and landings with seismic joints that accommodate drift. Design Drift = $D_{pI} = D_p \times (I_e)$, 1 unit = one individual stair per floor.	1
C3011.001b	Wall Finishes	Wall Partition, Type: Gypsum + Wallpaper, Partial Height, Fixed Below, Lateral Braced Above, 1 unit = 100 lineal feet	0.53

Table B-3 Representative Nonstructural Fragilities, Typical Floor, Non-Directional, Mid-Rise Office Occupancies, Risk Category II

ID	Group	Description	Normative Quantity
C3021.001q	Floor Finishes	Generic Floor Covering – Flooding of floor caused by failure of pipe – Office – Dry, 1 unit = 1 square foot	14,000
C3027.002	Floor Finishes	Raised Access Floor, seismically rated, 1 unit = 100 square feet.	10
C3032.003a	Suspended Ceilings	Suspended Ceiling, SDC D,E (I_p=1.0), Area (A): A < 250, vertical and lateral support, 1 unit = 250 square feet	12.6
C3032.003b	Suspended Ceilings	Suspended Ceiling, SDC D,E (I_p =1.0), Area (A): 250 < A < 1000, vertical and lateral support, 1 unit = 600 square feet	5.25
C3032.003c	Suspended Ceilings	Suspended Ceiling, SDC D,E (I_p =1.0), Area (A): 1000 < A < 2500, vertical and lateral support, 1 unit = 1800 square feet	3.5
C3034.002	Lighting	Independent Pendant Lighting – seismically rated, single unit	21
D1014.011	Elevators and Lifts (1)	Traction Elevator – Applies to most California Installations 1976 or later, most western states installations 1982 or later and most other U.S installations 1998 or later, single unit.	2
D2021.023a	Cold Water Service	Cold or Hot Potable Water Piping (dia > 2.5 inches), SDC D,E,F, PIPING FRAGILITY, 1 unit = 1000 lineal feet	0.21
D2021.023b	Cold Water Service	Cold or Hot Potable Water Piping (dia > 2.5 inches), SDC D,E,F, BRACING FRAGILITY, 1 unit = 1000 lineal feet	0.21
D2022.013a	Hot Water Service	Heating hot Water Piping – Small Diameter Threaded Steel - (2.5 inches in diameter or less), SDC D, E, or F, PIPING FRAGILITY, 1 unit = 1000 lineal feet	1.18
D2022.013b	Hot Water Service	Heating hot Water Piping – Small Diameter Threaded Steel - (2.5 inches in diameter or less), SDC D, E, or F, BRACING FRAGILITY, 1 unit = 1000 lineal feet	1.18

Table B-3 Representative Nonstructural Fragilities, Typical Floor, Non-Directional, Mid-Rise Office Occupancies, Risk Category II (continued)

ID	Group	Description	Normative Quantity
D2022.023a	Hot Water Service	Heating hot Water Piping – Large Diameter Welded Steel - (greater than 2.5 inches in diameter), SDC D, E, or F, PIPING FRAGILITY, 1 unit = 1000 lineal feet	0.42
D2022.023b	Hot Water Service	Heating hot Water Piping – Large Diameter Welded Steel - (greater than 2.5 inches in diameter), SDC D, E, or F, BRACING FRAGILITY, 1 unit = 1000 lineal feet	0.42
D2031.013b	Waste Piping	Sanitary Waste Piping - Cast Iron w/flexible couplings, SDC D,E,F, BRACING FRAGILITY, 1 unit = 1000 lineal feet	0.8
D3041.011c	HVAC	HVAC Galvanized Sheet Metal Ducting less than 6 sq. ft in cross sectional area, SDC D, E, or F, 1 unit = 1000 lineal feet	1.05
D3041.012c	HVAC	HVAC Galvanized Sheet Metal Ducting – 6 sq. ft cross sectional area or greater, SDC D, E, or F, 1 unit = 1000 lineal feet	0.28
D4011.023a	Fire Protection	Fire Sprinkler Water Piping - Horizontal Mains and Branches - Old Style Victaulic - Thin Wall Steel - Poorly designed bracing, SDC D, E, or F , PIPING FRAGILITY, 1 unit = 1000 lineal feet	2.8
D4011.053a	Fire Protection	Fire Sprinkler Drop Standard Threaded Steel – Dropping into braced lay-in tile SOFT ceiling – 6 ft. long drop maximum, SDC D, E, or F, 1 unit = 100 drops	1.26
D5012.023q	Low Tension Service	Risk Cat II-Low Voltage Switchgear – Capacity: 100 to <350 Amp – Equipment that is either hard anchored or is vibration isolated with seismic snubbers/restraints - Anchorage fragility only, unit = "each"	2

Notes: (1) Elevator and lift fragilities occur on the first floor only.

Table B-4 Representative Nonstructural Fragilities, Rooftop Mechanical Components, Mid-Rise Office Occupancies, Risk Category II

ID	Group	Description	Normative Quantity
D3031.013o	HVAC Equip.	Risk Cat II - x/h = 1.0 – Chiller – Capacity: 100 to <350 Ton – Equipment that is either hard anchored or is vibration isolated with seismic snubbers/restraints – Combined anchorage/isolator and equipment fragility, unit = "each"	2
D3031.023o	HVAC Equip.	Risk Cat II - x/h = 1 – Cooling Tower – Capacity: 100 to <350 Ton - Equipment that is either hard anchored or is vibration isolated with seismic snubbers/restraints – Combined anchorage/isolator and equipment fragility, unit = "each"	2
D3052.013n	HVAC Equip.	Risk Cat II x/h = 1.0 – Air Handling Unit - Capacity: 5000 to <10000 CFM – Equipment that is either hard anchored or is vibration isolated with seismic snubbers/restraints – Combined anchorage/isolator and equipment fragility, unit = "each"	6
D5012.013f	Low Tension Service	Risk Cat II x/h = 1.0 – Motor Control Center – Capacity: all – Equipment that is either hard anchored or is vibration isolated with seismic snubbers/restraints – Combined anchorage/isolator and equipment fragility, unit = "each"	3
D5012.023u	Low Tension Service	Risk Cat II – Low Voltage Switchgear – Capacity: 100 to <350 Amp - Equipment that is either hard anchored or is vibration isolated with seismic snubbers/restraints – Combined anchorage/isolator and equipment fragility, unit = "each"	2

Nonstructural components in Risk Category IV office archetypes (emergency operations centers) are the same, but specific fragilities were selected based on Risk Category IV seismic design criteria.

The quantity of components in a performance group was determined by the total number of components in a given direction, at a given floor level, divided by the fragility unit of measure. Some adjustments were made to the quantities obtained from the *Normative Quantity Estimation Tool*. Raised access floors were limited to 1000 square feet of floor area. Suspended ceiling systems were divided into 3 groups; 50 percent of the ceiling area was devoted to ceiling systems with areas from 1,000 to 2,500 square feet in area, 25 percent to ceiling systems between 250 and 1,000 square feet in area, and the remainder to systems 250 square feet or less in area. The number of pendant light fixtures was reduced, and most light fixtures in office occupancies were assumed to be recessed lights integrated into the ceiling system.

B.2 Healthcare Occupancies

Healthcare occupancies include general acute-care hospitals providing surgical, imaging, and laboratory services to patients staying longer than 24 hours, and outpatient medical facilities providing diagnostic imaging and outpatient surgeries to patients staying less than 24 hours. Performance groups and nonstructural component fragilities included for typical floors of representative mid-rise, Risk Category II, healthcare archetypes are provided in Tables B-5 through B-7. Performance groups and fragilities for rooftop mechanical equipment are provided in Table B-8.

Table B-5 Representative Nonstructural Fragilities, Typical Floor, Direction 1, Mid-Rise Healthcare Occupancies, Risk Category II

ID	Group	Description	Normative Quantity
B2022.035	Exterior Curtain Wall	Midrise stick-built curtain wall, Config: Monolithic, Lamination: Not laminated, Glass Type: Annealed, Details: 1/4 in. (6 mm) AN monolithic; glass-frame clearance = 0.43 in. (11 mm); aspect ratio = 2:1 sealant = dry, 1 unit = 30 SF	86.67
C1011.001b	Fixed Partitions	Wall Partition, Type: Gypsum with metal studs, Partial Height, Fixed Below, Lateral Braced Above, 1 unit = 100 lineal feet	4.29
C1011.001c	Fixed Partitions	Wall Partition, Type: Gypsum with metal studs, Full Height, Fixed Below, Slip Track Above with returns, 1 unit = 100 lineal feet	4.29
C2011.001i	Stairs	Prefabricated steel with steel treads and landings with seismic joints that accommodate drift. Design Drift = $D_{pI} = D_p \times (I_e)$, 1 unit = one individual stair per floor	1
C3011.001b	Wall Finishes	Wall Partition, Type: Gypsum + Wallpaper, Partial Height, Fixed Below, Lateral Braced Above, 1 unit = 100 lineal feet	0.89

Table B-6 Representative Nonstructural Fragilities, Typical Floor, Direction 2, Mid-Rise Healthcare Occupancies, Risk Category II

ID	Group	Description	Normative Quantity
B2022.035	Exterior Curtain Wall	Midrise stick-built curtain wall, Config: Monolithic, Lamination: Not laminated, Glass Type: Annealed, Details: 1/4 in. (6 mm) AN monolithic; glass-frame clearance = 0.43 in. (11 mm); aspect ratio = 2:1 sealant = dry, 1 unit = 30 SF	121.33
C1011.001b	Fixed Partitions	Wall Partition, Type: Gypsum with metal studs, Partial Height, Fixed Below, Lateral Braced Above, 1 unit = 100 lineal feet	3.06
C1011.001c	Fixed Partitions	Wall Partition, Type: Gypsum with metal studs, Full Height, Fixed Below, Slip Track Above with returns, 1 unit = 100 lineal feet	3.06
C2011.001i	Stairs	Prefabricated steel with steel treads and landings with seismic joints that accommodate drift. Design Drift = $D_{pI} = D_p \times (I_e)$, 1 unit = one individual stair per floor	1
C3011.001b	Wall Finishes	Wall Partition, Type: Gypsum + Wallpaper, Partial Height, Fixed Below, Lateral Braced Above, 1 unit = 100 lineal feet	0.89

Table B-7 Representative Nonstructural Fragilities, Typical Floor, Non-Directional, Mid-Rise Healthcare Occupancies, Risk Category II

ID	Group	Description	Normative Quantity
C3021.001r	Floor Finishes	Generic Floor Covering – Flooding of floor caused by failure of pipe – Hospital – Dry, 1 unit = 1 square foot	14,000
C3032.003a	Suspended Ceilings	Suspended Ceiling, SDC D,E (I_p=1.0), Area (A): A < 250, vertical and lateral support, 1 unit = 250 square feet	26.8
C3032.003b	Suspended Ceilings	Suspended Ceiling, SDC D,E (I_p =1.0), Area (A): 250 < A < 1000, vertical and lateral support, 1 unit = 600 square feet	5.6
C3032.003c	Suspended Ceilings	Suspended Ceiling, SDC D,E (I_p =1.0), Area (A): 1000 < A < 2500, vertical and lateral support, 1 unit = 1800 square feet	0.62
C3034.002	Lighting	Independent Pendant Lighting – seismically rated, single units	21
D1014.011	Elevators and Lifts	Traction Elevator – Applies to most California Installations 1976 or later, most western states installations 1982 or later and most other U.S installations 1998 or later, single units.	2
D2021.023a	Cold Water Service	Cold or Hot Potable Water Piping (dia > 2.5 inches), SDC D,E,F, PIPING FRAGILITY, 1 unit = 1000 lineal feet	0.56
D2021.023b	Cold Water Service	Cold or Hot Potable Water Piping (dia > 2.5 inches), SDC D,E,F, BRACING FRAGILITY, 1 unit = 1000 lineal feet	0.56
D2022.013a	Hot Water Service	Heating hot Water Piping – Small Diameter Threaded Steel - (2.5 inches in diameter or less), SDC D, E, or F, PIPING FRAGILITY, 1 unit = 1000 lineal feet	3.08
D2022.013b	Hot Water Service	Heating hot Water Piping – Small Diameter Threaded Steel – (2.5 inches in diameter or less), SDC D, E, or F, BRACING FRAGILITY, 1 unit = 1000 lineal feet	3.08

Table B-7 Representative Nonstructural Fragilities, Typical Floor, Non-Directional, Mid-Rise Healthcare Occupancies, Risk Category II (continued)

ID	Group	Description	Normative Quantity
D2022.023a	Hot Water Service	Heating hot Water Piping – Large Diameter Welded Steel – (greater than 2.5 inches in diameter), SDC D, E, or F, PIPING FRAGILITY, 1 unit = 1000 lineal feet	1.12
D2022.023b	Hot Water Service	Heating hot Water Piping – Large Diameter Welded Steel – (greater than 2.5 inches in diameter), SDC D, E, or F, BRACING FRAGILITY, 1 unit = 1000 lineal feet	1.12
D2031.013b	Waste Piping	Sanitary Waste Piping – Cast Iron w/flexible couplings, SDC D,E,F, BRACING FRAGILITY, 1 unit = 1000 lineal feet	2.10
D2061.013a	Steam Piping	Steam Piping – Small Diameter Threaded Steel – (2.5 inches in diameter or less), SDC D, E, or F, PIPING FRAGILITY, 1 unit = 1000 lineal feet	0.28
D2061.013b	Steam Piping	Steam Piping – Small Diameter Threaded Steel – (2.5 inches in diameter or less), SDC D, E, or F, BRACING FRAGILITY, 1 unit = 1000 lineal feet	0.28
D2061.023a	Steam Piping	Steam Piping – Large Diameter Welded Steel – (greater than 2.5 inches in diameter), SDC D, E, or F, PIPING FRAGILITY, 1 unit = 1000 lineal feet	0.42
D2061.023b	Steam Piping	Steam Piping – Large Diameter Welded Steel – (greater than 2.5 inches in diameter), SDC D, E, or F, BRACING FRAGILITY, 1 unit = 1000 lineal feet	0.42
D3041.011c	HVAC	HVAC Galvanized Sheet Metal Ducting less than 6 sq. ft in cross sectional area, SDC D, E, or F, 1 unit = 1000 lineal feet	1.05
D3041.012c	HVAC	HVAC Galvanized Sheet Metal Ducting – 6 sq. ft cross sectional area or greater, SDC D, E, or F, 1 unit = 1000 lineal feet	0.49
D4011.023a	Fire Protection	Fire Sprinkler Water Piping – Horizontal Mains and Branches – Old Style Victaulic – Thin Wall Steel – Poorly designed bracing, SDC D, E, or F , PIPING FRAGILITY, 1 unit = 1000 lineal feet	3.08
D4011.053a	Fire Protection	Fire Sprinkler Drop Standard Threaded Steel – Dropping into braced lay-in tile SOFT ceiling – 6 ft. long drop maximum, SDC D, E, or F, 1 unit = 100 drops	1.68
D5012.023q	Low Tension Service	Risk Cat II – Low Voltage Switchgear – Capacity: 100 to <350 Amp – Equipment that is either hard anchored or is vibration isolated with seismic snubbers/restraints – Anchorage fragility only, unit = "each"	6

Table B-8 Representative Nonstructural Fragilities, Rooftop Mechanical Components, Mid-Rise Healthcare Occupancies, Risk Category II

ID	Group	Description	Normative Quantity
D3031.013o	HVAC Equip.	Risk Cat II - x/h = 1.0 – Chiller – Capacity: 100 to <350 Ton - Equipment that is either hard anchored or is vibration isolated with seismic snubbers/restraints – Combined anchorage/isolator and equipment fragility, unit = "each"	2
D3031.023o	HVAC Equip.	Risk Cat II - x/h = 1 – Cooling Tower – Capacity: 100 to <350 Ton - Equipment that is either hard anchored or is vibration isolated with seismic snubbers/restraints – Combined anchorage/isolator and equipment fragility, unit = "each"	2
D3032.013n	HVAC Equip.	Compressor – Capacity: Small non-medical air supply – Equipment that is either hard anchored or is vibration isolated with seismic snubbers/restraints – Combined anchorage/isolator and equipment fragility, Risk Category II, SDC D, x/h = 1.00, unit = "each"	2
D3052.013n	HVAC Equip.	Risk Cat II x/h = 1.0 – Air Handling Unit – Capacity: 5000 to <10000 CFM – Equipment that is either hard anchored or is vibration isolated with seismic snubbers/restraints – Combined anchorage/isolator and equipment fragility, unit = "each"	8
D5012.013f	Low Tension Service	Risk Cat II x/h = 1.0 – Motor Control Center – Capacity: all – Equipment that is either hard anchored or is vibration isolated with seismic snubbers/restraints – Combined anchorage/isolator and equipment fragility, unit = "each"	4
D5012.023u	Low Tension Service.	Risk Cat II – Low Voltage Switchgear – Capacity: 100 to <350 Amp – Equipment that is either hard anchored or is vibration isolated with seismic snubbers/restraints – Combined anchorage/isolator and equipment fragility, unit = "each"	6
D5092.031m	Emergency Light and Power.	Risk Cat II – Diesel generator – Capacity: 100 to <350 kVA – Equipment that is either hard anchored or is vibration isolated with seismic snubbers/restraints – Combined anchorage/isolator and equipment fragility, unit = "each"	2

Nonstructural and medical component fragilities for Risk Category II archetypes (non-acute care outpatient medical buildings) and Risk Category IV archetypes (general acute care hospitals) were assumed to be identical except for seismic design criteria. In general, however, the types and quantities of nonstructural components and medical equipment would differ between outpatient medical buildings and general acute care hospital buildings, especially for equipment associated with surgical services.

B.2.1 Medical Equipment

Building performance models for healthcare occupancies include fragilities for fixed and mobile medical equipment. Performance groups, quantities, and types of medical equipment fragilities included on each floor of representative mid-rise, Risk Category II, healthcare archetypes are provided in Tables B-9 through B-12. Medical equipment in Risk Category IV healthcare archetypes (acute care hospitals) was assumed to be the same, but fragilities were designed for Risk Category IV seismic criteria.

Table B-9 Medical Equipment Fragilities, First Floor, Non-Directional, Mid-Rise Healthcare Occupancies, Risk Category II

ID	Description	Quantity
E1028.021a	Endoscope System	3
E1028.022b	Light System – Risk Category II, SDC D, $x/h = 0 - 0.0833$	36
E1028.023a	Ultrasound Unit	2
E1028.203b	Freezer – Risk Category II, SDC D, $x/h = 0 - 0.1667$	1
E1028.212b	Breathing Circuit Dryer – Risk Category II, SDC D, $x/h = 0$	1
E1028.311d	Ice Dispenser – Risk Category II, SDC D, $x/h = 0 - 0.4$	1
E1028.321d	Under Counter Refrigerator – Risk Category II, SDC D, $x/h = 0 - 0.4$	1
E1028.331c	Refrigerator – Risk Category II, SDC D, $x/h = 0 - 0.2$	1
E1028.341d	Med Station – Risk Category II, SDC D, $x/h = 0 - 0.4$	1
E1028.401b	Imaging System (CT) – Risk Category II, SDC D, $x/h = 0$	1
E1028.403b	CT C-Arm – Risk Category II, SDC D $x/h = 0$	1
E1028.411b	MRI System – Risk Category II, SDC D, $x/h = 0$	1
E1028.421b	Laser Imaging – Risk Category II, SDC D, $x/h = 0 - 0.0833$	1
E1028.431b	X-Ray System – Risk Category II, SDC D, $x/h = 0 - 0.0833$	1
E1028.501c	Shelving System – Risk Category II, SDC D, $x/h = 0 - 0.1667$	10

Table B-10 Medical Equipment Fragilities, Second Floor, Non-Directional, Mid-Rise Healthcare Occupancies, Risk Category II

ID	Description	Quantity
E1028.001a	Anesthesia Machine	4
E1028.002a	Balloon Pump	2
E1028.003a	Catheter Cabinet	1
E1028.004a	Blood Recovery System	1
E1028.005a	Hypothermia System	2
E1028.006a	Surgical Table	4
E1028.011a	Patient Bed	6
E1028.101d	Equipment Boom – Risk Category II, SDC D, x/h = 0.2 – 0.25	4
E1028.102d	Warming Cabinet – Risk Category II, SDC D, x/h = 0.2 – 0.25	4
E1028.103d	Anesthesia Boom – Risk Category II, SDC D, x/h = 0.2 – 0.25	4
E1028.104a	Ice Slusher	1
E1028.105d	Dual Surgical Light – Risk Category II, SDC D, x/h = 0.2 – 0.25	4
E1028.106d	Cath Lab System – Risk Category II, SDC D, x/h = 0.2 – 0.25	1
E1028.107d	Sterilizer – Risk Category II, SDC D, x/h = 0.2 – 0.25	2
E1028.108d	Washer/Disinfector – Risk Category II, SDC D, x/h = 0.2 – 0.25	1
E1028.202d	Ultrasonic Cleaner – Risk Category II, SDC D, x/h = 0.1667 – 0.2	1
E1028.205d	Decontamination Washer – Risk Category II, SDC D, x/h = 0.1667 – 0.2	1
E1028.301c	Headwall – Risk Category II, SDC D, x/h = 0 – 0.5	6
E1028.311d	Ice Dispenser – Risk Category II, SDC D, x/h = 0 – 0.4	1
E1028.321d	Under Counter Refrigerator – Risk Category II, SDC D, x/h = 0 – 0.4	2
E1028.331c	Refrigerator – Risk Category II, SDC D, x/h = 0 – 0.2	1
E1028.341d	Medstation – Risk Category II, SDC D, x/h = 0 – 0.4	1

Table B-11 Medical Equipment Fragilities, Third Floor (Fourth Floor Similar), Non-Directional, Mid-Rise Healthcare Occupancies, Risk Category II

ID	Description	Quantity
E1028.011a	Patient Bed	12
E1028.301c	Headwall – Risk Category II, SDC D, x/h = 0-0.5	12
E1028.311f	Ice Dispenser – Risk Category II, SDC D, x/h = 0.6	1
E1028.321f	Under Counter Refrigerator – Risk Category II, SDC D, x/h = 0.6	2
E1028.341f	Medstation – Risk Category II, SDC D, x/h = 0.6	1

Table B-12 Medical Equipment Fragilities, Fifth Floor, Non-Directional, Mid-Rise Healthcare Occupancies, Risk Category II

ID	Description	Quantity
E1028.031a	Cryostat	1
E1028.201d	Bio Safety Hood – Risk Category II, SDC D x/h = 0.8	2
E1028.204d	Laminar Flow Hood – Risk Category II, SDC D, x/h =0.8	1
E1028.221d	Chemistry Analyzer – Risk Category II, SDC D, x/h = 0.8	1
E1028.331d	Refrigerator – Risk Category II, SDC D, x/h = 0.8	2
E1028.501d	Shelving System – Risk Category II, SDC D, x/h = 0.8	5

B.2.2 Medical Equipment Fragility and Consequence Data

Medical equipment fragility and consequence data are not available in the default PACT fragility database. Fragility and consequence data for fixed and mobile medical equipment used in this study are summarized in Table B-13 and Table B-14.

Fixed (i.e., anchored) components are acceleration-controlled, and median capacities are user-defined, determined as described in Section 4.5.3. The component importance factor, I_p, for fixed medical components was set to 1.5 for acute-care hospital archetypes and 1.0 for outpatient medical archetypes. Mobile components are velocity-controlled, and median capacities were determined as described in Section 4.5.4. All mobile units were assumed to have locked steel casters on floors with a "slick" surface (e.g., poly/tetra/fluoro/ethylene-to-steel surface). All medical components are assumed to have identical response characteristic in each orthogonal direction, and were classified as non-directional in the performance models.

Each medical component was assigned two mutually exclusive damage states. In all cases, damage State 1 (DS1) has an 80 percent probability of occurrence, and the component is assumed to be damaged but repairable at a cost of 10 percent of the replacement cost. Damage State 2 (DS2) has a 20 percent probability of occurrence, and the component is assumed to be damaged beyond repair. The dispersion, β, for all medical components was set to 0.5.

Repair and replacement costs were based on available or estimated list price data for typical medical equipment. Repair costs were taken as 10% of replacement cost. Replacement costs consider only the cost of the component, and do not include ancillary work required to access or reinstall the damaged component. Repair times range from 7 to 180 days, depending on the damage state and the cost and complexity of the component. Replacement costs and repair times for medical components are judgement-based estimates, and should be taken as lower bound values.

Table B-13 Medical Equipment Fragility Data

ID	Unit	Attach.	Demand Parameter	DS1 Damage Descrip.	DS1 Probability	DS2 Damage Descrip.	DS2 Probability	Dispersion β
Various	Various	Mobile	Velocity	Damaged, Repairable	0.8	Damaged, Irreparable	0.2	0.5
Various	Various	Fixed	Acceleration	Damaged, Repairable	0.8	Damaged, Irreparable	0.2	0.5

Table B-14 Medical Equipment Consequence Data

ID	Unit	Attach.	Replace. Cost	DS1 Repair Descrip.	DS1 Repair Cost (%)	DS1 Repair Time (days)	DS2 Repair Descrip.	DS2 Repair Cost (%)	DS2 Repair Time (days)
E1028.001	Anesthesia Machine	Mobile	$78,344	Repair	10%	7	Replace	100%	30
E1028.002	Ballon Pump	Mobile	$70,448	Repair	10%	7	Replace	100%	30
E1028.003	Catheter Cabinet	Mobile	$5,432	Repair	10%	7	Replace	100%	30
E1028.004	Blood Recovery System	Mobile	$52,640	Repair	10%	7	Replace	100%	30
E1028.005	Hypothermia System	Mobile	$45,786	Repair	10%	7	Replace	100%	30
E1028.006	Surgical Table	Mobile	$57,254	Repair	10%	7	Replace	100%	30
E1028.011	Patient Bed	Mobile	$53,592	Repair	10%	7	Replace	100%	30

Table B-14 Medical Equipment Consequence Data (continued)

ID	Unit	Attach.	Replace. Cost	DS1 Repair Descrip.	DS1 Repair Cost (%)	DS1 Repair Time (days)	DS2 Repair Descrip.	DS2 Repair Cost (%)	DS2 Repair Time (days)
E1028.021	Endoscope System	Mobile	$35,280	Repair	10%	7	Replace	100%	30
E1028.022	Light System	Fixed	$12,962	Repair	10%	7	Replace	100%	30
E1028.023	Ultrasound Unit	Mobile	$174,720	Repair	10%	7	Replace	100%	30
E1028.031	Cryostat	Mobile	$27,944	Repair	10%	7	Replace	100%	30
E1028.101	Equipment Boom	Fixed	$33,992	Repair	10%	14	Replace	100%	60
E1028.102	Warming Cabinet (full height)	Fixed	$18,122	Repair	10%	14	Replace	100%	60
E1028.103	Anesthesia Boom	Fixed	$23,912	Repair	10%	14	Replace	100%	60
E1028.104	Ice Slusher	Mobile	$72,744	Repair	10%	14	Replace	100%	60
E1028.105	Dual Surgical Light	Fixed	$38,080	Repair	10%	14	Replace	100%	60
E1028.106	Cath Lab System	Fixed	$3,348,800	Repair	10%	30	Replace	100%	180
E1028.107	Sterilizer	Fixed	$179,380	Repair	10%	14	Replace	100%	60
E1028.108	Washer/ Disinfector	Fixed	$ 134,064	Repair	10%	14	Replace	100%	60
E1028.201	Bio Safety Hood (4 ft.)	Fixed	$19,936	Repair	10%	7	Replace	100%	30
E1028.202	Ultrasonic Cleaner (table top, 5.75 gal.)	Fixed	$3,640	Repair	10%	7	Replace	100%	30
E1028.203	Freezer (23.3 cu. ft.)	Fixed	$7,616	Repair	10%	7	Replace	100%	30
E1028.204	Laminar Flow Hood (6 ft.)	Fixed	$8,652	Repair	10%	7	Replace	100%	30
E1028.205	Decontamin. Washer	Fixed	$28,000	Repair	10%	7	Replace	100%	30
E1028.212	Breathing Circuit Dryer (single cabinet)	Fixed	$10,248	Repair	10%	7	Replace	100%	30
E1028.221	Chemistry Analyzer	Fixed	$436,181	Repair	10%	14	Replace	100%	60
E1028.301	Headwall	Fixed	$5,264	Repair	10%	7	Replace	100%	30
E1028.311	Ice Dispenser	Fixed	$8,400	Repair	10%	7	Replace	100%	30
E1028.321	Under Counter Refrigerator	Fixed	$2,464	Repair	10%	7	Replace	100%	30
E1028.331	Refrigerator (49 cu. ft.)	Fixed	$8,208	Repair	10%	7	Replace	100%	30

Table B-14 Medical Equipment Consequence Data (continued)

ID	Unit	Attach.	Replace. Cost	DS1			DS2		
				Repair Descrip.	Repair Cost (%)	Repair Time (days)	Repair Descrip.	Repair Cost (%)	Repair Time (days)
E1028.341	Medstation (6-drawer)	Fixed	$62,227	Repair	10%	14	Replace	100%	60
E1028.401	Imaging System (16 slice CT)	Fixed	$1,164,800	Repair	10%	30	Replace	100%	180
E1028.403	CT C-Arm (digital)	Fixed	$252,000	Repair	10%	30	Replace	100%	180
E1028.411	Mri System	Fixed	$2,475,200	Repair	10%	30	Replace	100%	180
E1028.421	Laser Imaging	Fixed	$ 78,400	Repair	10%	7	Replace	100%	30
E1028.431	X-Ray System (digital)	Fixed	$655,200	Repair	10%	30	Replace	100%	180
E1028.501	Shelving System (single 5 ft. unit)	Fixed	$1,316	Repair	10%	7	Replace	100%	30

Appendix C
Performance Estimation Tool User Manual

Results of system-specific FEMA P-58 performance assessments are summarized in Chapter 5. Data are available for each performance metric, by system, occupancy, Risk Category, building height, hazard level, and intensity level. The *Performance Estimation Tool* (PET) was initially created as a vehicle for viewing assessment data and analyzing trends in results. It serves as a permanent repository of assessment data and can also be used as a tool for preliminary performance-based design. It is provided in FEMA P-58, Volume 3, *Supporting Electronic Materials and Background Documentation*.

This appendix provides instructions for using the *Performance Estimation Tool* to access and view available performance assessment results. Instructions for using the tool as a design aid are provided in FEMA P-58, Volume 6, *Guidelines for Performance-Based Seismic Design of Buildings*.

C.1 Introduction

The *Performance Estimation Tool* requires, as input, the selection of seismic force-resisting system, occupancy type, Risk Category, building height, and seismic hazard from the available options. It also requires selection of design story drift and design strength in terms of a multiple of minimum base shear. Based on the selected parameters, the tool will return graphs and detailed plots of performance assessment results contained within the database.

C.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 gray-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.

C.3 User Interface Tab

Figure C-1 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 C-2 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.

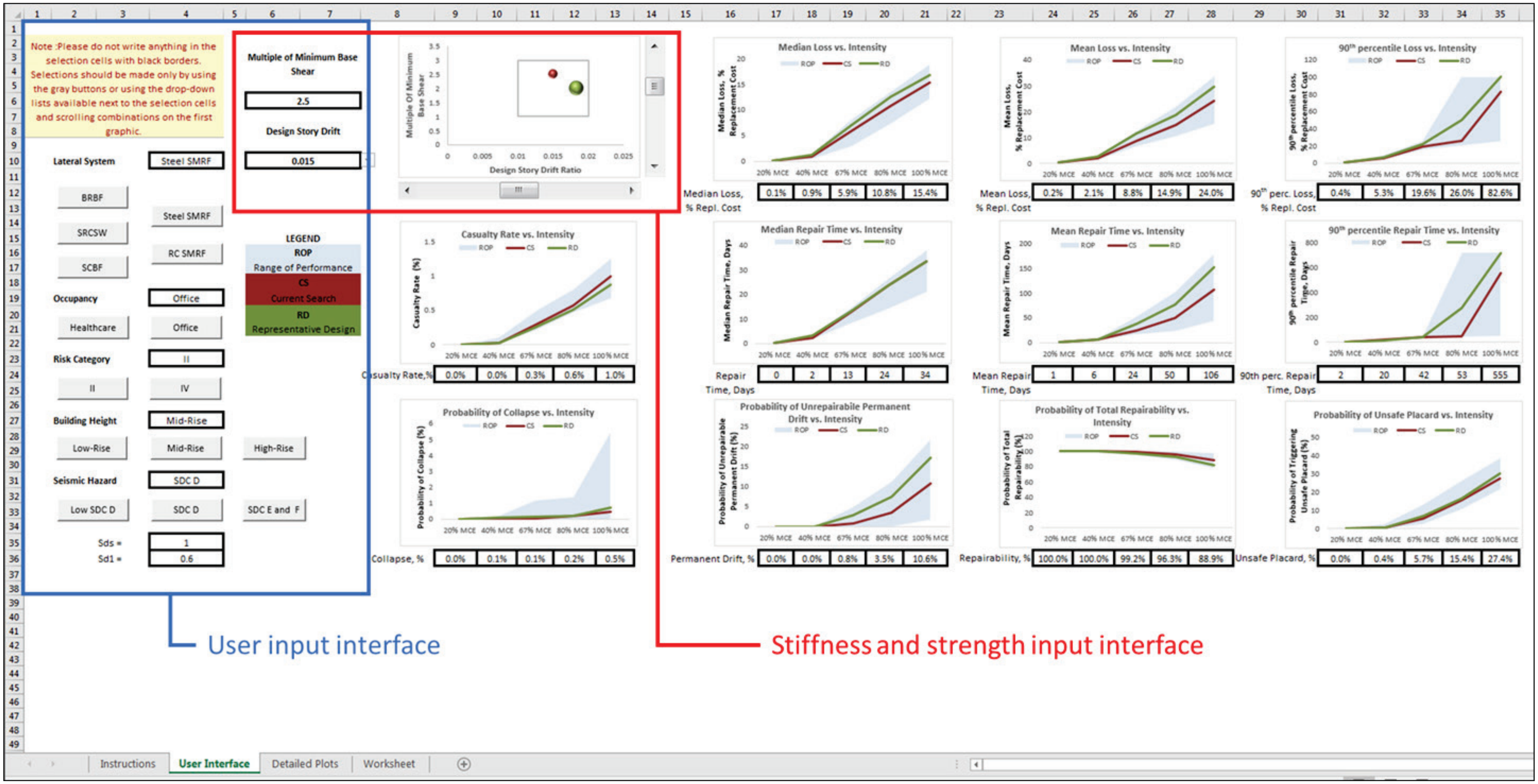


Figure C-1 PET User Interface tab.

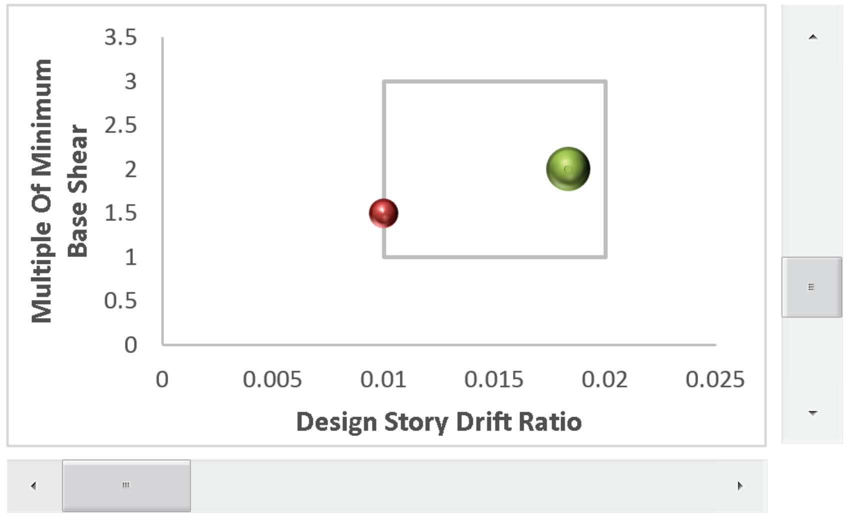
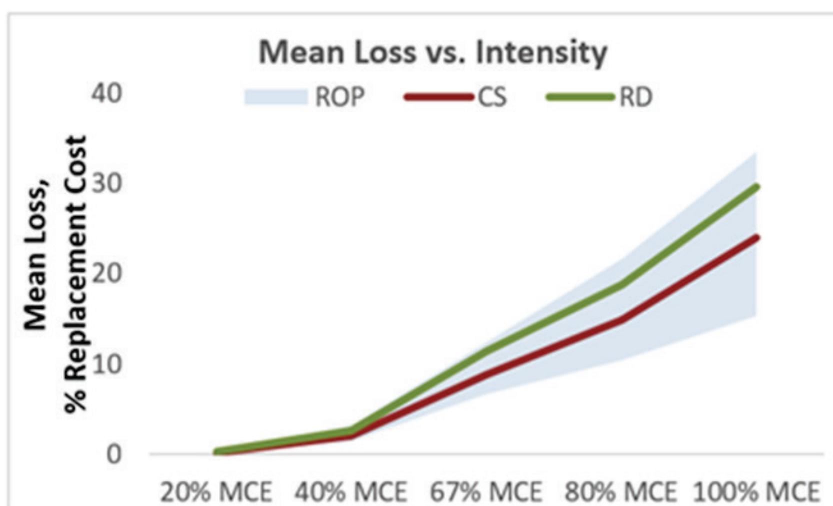


Figure C-2 Stiffness and strength input interface and design space graphic on the User Interface tab.

Figure C-3 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.

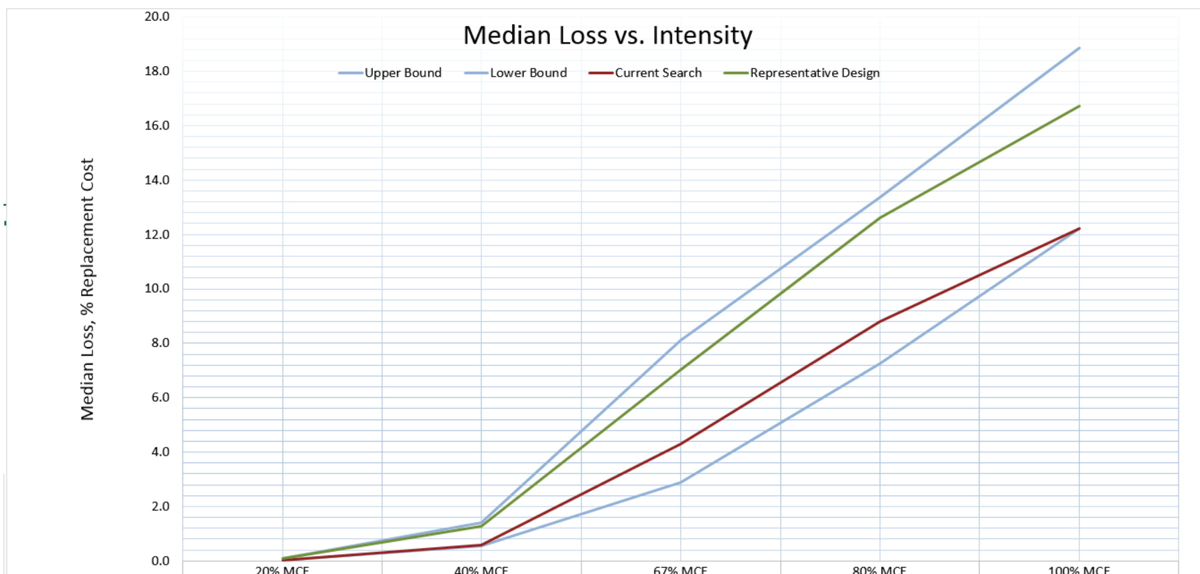


Mean Loss, % Repl. Cost	0.2%	2.1%	8.8%	14.9%	24.0%

Figure C-3 Graph showing mean repair cost as a percentage of replacement cost on the User Interface tab.

C.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 C-4 provides a detailed plot of mean repair cost versus intensity, which is a more detailed version of the information shown in Figure C-3. Similar to Figure C-3, 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	0.1	1.4	8.1	13.4	18.8
Lower Bound	0.0	0.5	2.9	7.3	12.2
Current Search	0.0	0.6	4.3	8.8	12.2
Representative Design	0.1	1.3	7.0	12.6	16.7

Figure C-4 Detailed plot of mean repair cost versus intensity.

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