Next-Generation Performance-Based Seismic Design Guidelines

Program Plan for New and Existing Buildings

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Next-Generation Performance-Based Seismic Design Guidelines

Program Plan for New and Existing Buildings

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Notice

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Foreword

One of the primary goals of the Department of Homeland Security's Federal Emergency Management Agency (FEMA) is prevention or mitigation of this country's losses from hazards that affect the built environment. To achieve this goal, we as a nation must determine what level of performance is expected from our buildings during a severe event, such as an earthquake, blast, or hurricane. To do this, FEMA contracted with the Applied Technology Council (ATC) to develop next-generation performance-based seismic design procedures and guidelines, which would allow engineers and designers to better work with stakeholders in identifying the probable seismic performance of new and existing buildings. These procedures could be voluntarily used to: (1) assess and improve the performance of buildings designed to a building code "life safety" level, which would, in all likelihood, still suffer significant structural and nonstructural damage in a severe event; and (2) more effectively meet the performance targets of current building codes by providing verifiable alternatives to current prescriptive code requirements for new buildings.

This FEMA 445 Program Plan builds on earlier plans developed for FEMA by the Earthquake Engineering Research Institute, and the Earthquake Engineering Research Center. As a basis for this plan, FEMA 349 (EERI, 2000) provided a description of the key activities necessary for developing performance-based seismic design criteria, and FEMA 283 (EERC, 1996) emphasized the research that would be required.

This Program Plan is based on the results of a workshop soliciting the input of the nation's leading seismic professionals in preparing a long-term plan to develop new performance-based seismic design procedures. It does an excellent job of capturing the recommendations from that workshop and describing the necessary requirements. Execution of the plan, however, is contingent upon funding, and FEMA had concerns regarding the availability of funding at the levels necessary to achieve the ambitious goals outlined in the plan. As a result, FEMA and ATC developed a reduced scope and extended schedule under which the program could proceed with less than full funding. This Program Plan includes the projected costs for both the original and modified-scope programs.

Publication of this Program Plan does not obligate FEMA or any other federal agency to any portion of the plan contained herein. The information and opinions contained in this Program Plan are solely those of the project participants, and do not necessarily represent the views of FEMA.

FEMA wishes to express its sincere gratitude to all who were involved in this project and in the development of this Program Plan. The result of their hard work and dedication will play an important role in helping the nation move towards performance-based seismic design and reducing losses suffered by the citizenry in future earthquakes.

—Federal Emergency Management Agency

Preface

Advancement of present-generation performance-based seismic design procedures is widely recognized in the earthquake engineering community as an essential next step in the nation's drive to develop resilient, loss-resistant communities. This Program Plan offers a step-by-step, task-oriented program that will develop next-generation performance-based seismic design procedures and guidelines for structural and nonstructural components in new and existing buildings.

This FEMA 445 Program Plan is a refinement and extension of two earlier FEMA plans: FEMA 283 *Performance-Based Seismic Design of Buildings – an Action Plan*, which was prepared by the Earthquake Engineering Research Center, University of California at Berkeley in 1996, and FEMA 349 *Action Plan for Performance Based Seismic Design*, which was prepared by the Earthquake Engineering Research Institute in 2000. The state of practice for performance-based assessment, performance-based design of new buildings, and performance-based upgrades of existing buildings will all be significantly advanced under this Program Plan.

The preparation of this Program Plan, and developmental work completed to date, has been performed by the Applied Technology Council (ATC) under the ATC-58 project entitled *Development of Next-Generation Performance-Based Seismic Design Guidelines for New and Existing Buildings*. The technological framework developed under this program is transferable and can be adapted for use in performance-based design for other extreme hazards including fire, wind, flood, and terrorist attack. The decision-making tools and guidelines developed under this Program Plan will greatly improve our ability to develop cost-effective and efficient earthquake loss reduction programs nationwide.

Christopher Rojahn, ATC Executive Director

Acknowledgments

This FEMA-445 Program Plan was prepared by the Applied Technology Council under FEMA contract EMW-2001-CO-0378. Ronald O. Hamburger, Project Technical Director, was the principal architect of the Program Plan and is the principal author of this report. Substantial contributions were also made by the Product Development Team Leaders and their teams, with review and input by the Project Management Committee, and the Project Steering Committee.

The Project Management Committee consisted of Christopher Rojahn (Chair), Ronald O. Hamburger (Co-Chair), Peter J. May, Jack P. Moehle, Maryann T. Phipps (ATC Board Representative), and Jon Traw. The Structural Products Development Team consisted of Andrew Whittaker (Team Leader), Gregory Deierlein, Andre Filiatrault, John Hooper, and Andrew T. Merovich. The Nonstructural Performance Products Team consisted of Robert E. Bachman (Team Leader), David Bonowitz, Philip J. Caldwell, Andre Filiatrault, Robert P. Kennedy, Gary McGavin, Eduardo Miranda, and Keith Porter. The Risk Management Products Team consisted of Craig D. Comartin (Team Leader), Brian J. Meacham (Associate Team Leader), C. Allin Cornell, and Charles Kircher. Project Steering Committee members consisted of William T. Holmes (Chair), Daniel P. Abrams, Deborah B. Beck, Randall Berdine, Roger D. Borcherdt, Jimmy Brothers, Michel Bruneau, Terry Dooley, Mohammed Ettouney, John Gillengerten, William J. Petak, Randy Schreitmueller, and James W. Sealy. Jon A. Heintz served as Report Editor, and Peter N. Mork produced the camera-ready document. The affiliations of these individuals are provided in the list of project participants at the end of this report.

Input to this Program Plan was provided by a broad range of earthquake engineering specialists during a FEMA-sponsored workshop conducted by ATC in February 2003. Participants included researchers and practicing structural engineers as well policy makers and regulators. The sage advice provided by these individuals substantially influenced the direction and scope of this Program Plan.

The vision, insight, and patience provided by the FEMA Project Officer, Michael Mahoney, and the FEMA Technical Monitor, Robert D. Hanson, are also gratefully acknowledged.

Executive Summary

The Applied Technology Council (ATC), under the sponsorship of the Department of Homeland Security's Federal Emergency Management Agency (FEMA), is currently engaged in a project to advance the state of practice in performance-based seismic design. This report, FEMA 445 Program Plan, offers a step-by-step, task-oriented program that will develop next-generation performance-based seismic design procedures and guidelines for structural and nonstructural components in new and existing buildings. The preparation of this Program Plan, and developmental work completed to date, has been performed under the ATC-58 project entitled *Development of Next-Generation Performance-Based Seismic Design Guidelines for New and Existing Buildings*.

This Program Plan offers background on current code design procedures, introduces performance-based seismic design concepts, identifies improvements needed in current seismic design practice, and outlines the tasks and projected costs for a two-phase program to develop next-generation performance-based seismic design procedures and guidelines. This plan is a refinement and extension of two earlier FEMA plans: FEMA 283 *Performance-Based Seismic Design of Buildings – an Action Plan*, which was prepared by the Earthquake Engineering Research Center, University of California at Berkeley in 1996, and FEMA 349 *Action Plan for Performance Based Seismic Design*, which was prepared by the Earthquake Engineering Research Institute in 2000.

Building Code Procedures for Seismic Design

Building codes establish minimum requirements for safety through the specification of prescriptive criteria that regulate acceptable materials of construction, identify approved structural and nonstructural systems, specify required minimum levels of strength and stiffness, and control the details of how a building is to be put together. Although these prescriptive criteria are intended to result in buildings capable of providing certain levels of performance, the actual performance of individual building designs is not assessed as part of the traditional code design process. As a result, the performance capability of buildings designed to these prescriptive criteria can be better than the minimum standards anticipated by the code, while the performance of others could be worse.

Performance-based Design

Performance-based seismic design explicitly evaluates how a building is likely to perform, given the potential hazard it is likely to experience, considering uncertainties inherent in the quantification of potential hazard and uncertainties in assessment of the actual building response. It permits design of new buildings or upgrade of existing buildings with a realistic understanding of the risk of casualties, occupancy interruption, and economic loss that may occur as a result of future earthquakes.

It also establishes a vocabulary that facilitates meaningful discussion between stakeholders and design professionals on the development and selection of design options. It provides a framework for determining what level of safety and what level of property protection, at what cost, are acceptable to building owners, tenants, lenders, insurers, regulators and other decision makers based upon the specific needs of a project.

In contrast to prescriptive design approaches, performance-based design provides a systematic methodology for assessing the performance capability of a building, system or component. It can be used to verify the equivalent performance of alternatives, deliver standard performance at a reduced cost, or confirm higher performance needed for critical facilities.

First-generation procedures introduced the concept of performance in terms of discretely defined performance levels with names intended to connote the expected level of damage: Collapse, Collapse Prevention, Life Safety, Immediate Occupancy, and Operational Performance. They also introduced the concept of performance related to damage of both structural and nonstructural components. Performance Objectives were developed by linking one of these performance levels to a specific level of earthquake hazard. Although intended for existing buildings, these procedures are being extrapolated for use in the performance-based design of new buildings.

The Need for Next-Generation Procedures

As the state of knowledge and experience base advances, limitations in present-generation procedures are being identified by researchers and practitioners. These include questions regarding the accuracy of analytical procedures in predicting actual building response, questions regarding the level of conservatism present in acceptance criteria, the inability to reliably and economically apply performance-based procedures to the design of new buildings, and the need for alternative ways of communicating performance to stakeholders that is more meaningful and useful for decision-making purposes. Next-generation performance-based design procedures are needed to:

- Revise the discrete performance levels defined in first-generation procedures to create new performance measures (e.g. repair costs, casualties, and time of occupancy interruption) that better relate to the decision-making needs of stakeholders, and that communicate these losses in a way that is more meaningful to stakeholders.
- Create procedures for estimating probable repair costs, casualties, and time of occupancy interruption, for both new and existing buildings.
- Develop a framework for performance assessment that properly accounts for, and adequately communicates to stakeholders, limitations in our ability to accurately predict response, and uncertainty in the level of earthquake hazard.

Framework for Next-Generation Procedures

The next-generation performance-based seismic design procedures developed under this Program Plan will express performance directly in terms of quantified risks that a building owner or decision maker will be able to understand. Stakeholders prefer to define these risks in terms of the potential for casualties, repair costs, and occupancy interruption. Stakeholder guidance will be developed to assist decision makers in selecting appropriate levels of risk as the basis of design and upgrade projects. Engineering guidelines will be prepared to assist design professionals in developing building designs that are reliable and capable of meeting the selected risk criteria.

Program Plan

Work under this Program Plan is divided into two phases:

- *Phase 1: Developing a Methodology for Assessing the Seismic Performance of Buildings.* In this phase, a methodology will be developed for assessing the probable seismic performance of individual buildings in future earthquakes.
- *Phase 2: Developing Performance-Based Seismic Design Procedures and Guidelines.* In this phase, seismic design procedures and guidelines will be developed to assist engineers in designing buildings to meet desired performance goals, and to assist stakeholders in taking advantage of the benefits of performance-based design.

Work in each phase is organized around six broad categories of work: Planning and Management Program; Structural Performance Products; Nonstructural Performance Products; Risk Management Products; Guidelines Products; and Stakeholders Guide Products. Work in each technical area will be performed by one of three Product Development Teams, consisting of the Structural Performance Products Team, the Nonstructural Performance Products Team, and the Risk Management Products Team.

Planning and Management Program tasks will be carried out within a project management structure consisting of three committees: Project Management Committee, Project Technical Committee, and Project Steering Committee. Collectively, these committees provide management, technical oversight, and control of the work performed by the three Product Development Teams.

Projected Costs and Schedule

As originally planned, the total projected project costs of Phase 1 and 2 of this Program Plan are estimated to be approximately $21 million in 2004 dollars. Estimates of personnel and other costs were developed using prevailing labor costs common to projects of this type at the time this plan was prepared, and do not include escalation due to changes in the value of money, labor rates, internal government costs, or inflation. Phase 1 has a projected cost of approximately $11 million, and Phase 2 has a projected cost of approximately $10 million. At this funding level, each phase will last approximately five years, and the work of Phase 1 will be substantially complete before Phase 2 begins.

Since available funding was not adequate to support the full Program Plan, a reduced scope and extended schedule was developed under which the program could proceed with less than full funding. Projected costs for the modified-scope program are approximately 50% of those for the original program. Each phase is planned to be accomplished in approximately five to seven years, and Phase 1 has been underway for four years. Phase 2 is planned to begin upon completion of Phase 1.

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Chapter 1
Introduction

1.1 General

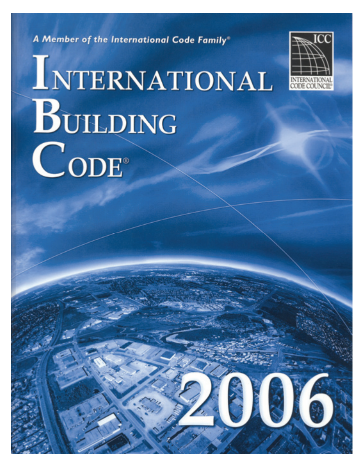
This report, FEMA 445 Program Plan, has been prepared to guide the development of next-generation performance-based seismic design procedures and guidelines applicable to new and existing buildings. It sets forth objectives, tasks, recommended budgets, and a schedule to be used as a basis for the execution of a project that builds on existing concepts for performance-based seismic design, and formulates a framework for a next-generation methodology. Work under this plan is being performed for the Department of Homeland Security's Federal Emergency Management Agency (FEMA) by the Applied Technology Council (ATC) under the ATC-58 project, *Development of Next-Generation Performance-Based Seismic Design Guidelines for New and Existing Buildings*.

Chapter 1 offers background on current code design procedures, performance-based seismic design, and improvements needed in current seismic design practice. Chapter 2 discusses project goals and organization. Chapters 3 and 4 present the basic work plan for implementing Phase 1, which will develop guidelines for improved procedures to assess the probable seismic performance of buildings. Chapters 5 and 6 present the work plan for implementing Phase 2, which will develop recommended performance objectives and guidelines for assisting engineers and stakeholders in implementing the performance-based design process.

Appendix A describes the technical details of the framework for next-generation seismic performance assessment, and introduces terms discussed in this Program Plan that may be less familiar to earthquake professionals who are not structural reliability or seismic risk specialists. Appendices B and C offer alternative numerical examples for implementing these procedures.

1.2 Current Building Code Procedures for Seismic Design

Design and construction in the United States is generally regulated at the state or local level using codes based on national model building codes and standards. When adopted and enforced by local authorities, building codes are intended to establish minimum requirements for providing safety to life and property from fire and other hazards (ICC, 2006).



This goal is accomplished through the specification of prescriptive criteria that regulate acceptable materials of construction, identify approved structural and nonstructural systems, specify required minimum levels of strength and stiffness, and control the details of how a building is to be put together. Prescriptive requirements are based on broad classifications of buildings and occupancies, and are typically stated in terms of fixed values such as fire resistance ratings, allowable area and height, and specifications related to structural design (e.g., dead loads, live loads, snow loads, rain loads, earthquake loads, wind loads, etc.).

Although the prescriptive criteria of model building codes are intended to result in buildings capable of providing certain levels of performance, the actual performance capability of individual building designs is not assessed as part of the traditional code design process. As a result, the performance capability of buildings designed to prescriptive criteria can be variable and, for a given building, may not be specifically known. The performance of some buildings designed to these prescriptive criteria can be better than the minimum standards anticipated by the code, while the performance of others could be worse.

The development of seismic design criteria is an ongoing process of improvement. The evolution of seismic design provisions in model building codes can be tracked against the occurrence of damaging earthquakes, both in the United States and abroad. Earthquakes in the early part of the 20th century (e.g. the 1925 Santa Barbara and 1933 Long Beach earthquakes) led to the development of regulations to provide for minimum levels of lateral strength. In the latter part of the 20th century earthquakes such as the 1971 San Fernando Earthquake led to the realization that, in addition to strength, buildings needed to have the ability to deform without catastrophic failure (a characteristic known as ductility).


Relatively new apartment complex damaged in the 1994 Northridge Earthquake

Building owners and occupants generally believe that adherence to building codes provides for a safe and habitable environment, and anticipated degrees of damage are not a normal consideration for owners and most design professionals. Experience in earthquakes at the end of the 20th century (e.g. the 1994 Northridge and 1995 Kobe Earthquakes) has forced recognition that damage, sometimes severe, can occur in buildings designed in accordance with the code. Property and insured losses as a result of the Northridge Earthquake, recognized as the most costly earthquake in U.S. history, led to an awareness that the level of structural and nonstructural damage that could occur in code-compliant buildings may not be consistent with public notions of acceptable performance.

Changes in the state of knowledge and the evolution of seismic design criteria have also led to changes in engineering practice and research. With an emphasis on providing stakeholders the information needed to make rational business or safety-related decisions, practice has moved toward predictive methods for assessing potential seismic performance. At the same time researchers have been working on the development of new analytical tools and test data needed to improve assessment techniques. Recognition that code-based strength and ductility requirements applicable for the design of new buildings are not suitable for the evaluation and upgrade of existing buildings has led to the development of performance-based engineering methods for seismic design.

1.3 Performance-Based Seismic Design

The performance-based seismic design process explicitly evaluates how a building is likely to perform, given the potential hazard it is likely to experience, considering uncertainties inherent in the quantification of potential hazard and uncertainties in assessment of the actual building response.

In performance-based design, identifying and assessing the performance capability of a building is an integral part of the design process, and guides the many design decisions that must be made. Figure 1-1 shows a flowchart that presents the key steps in the performance-based design process. It is an iterative process that begins with the selection of performance objectives, followed by the development of a preliminary design, an assessment as to whether or not the design meets the performance objectives, and finally redesign and reassessment, if required, until the desired performance level is achieved.

Performance-based design begins with the selection of design criteria stated in the form of one or more performance objectives. Each performance objective is a statement of the acceptable risk of incurring specific levels of damage, and the consequential losses that occur as a result of this damage, at a specified level of seismic hazard.

Losses can be associated with structural damage, nonstructural damage, or both. They can be expressed in the form of casualties, direct economic costs, and downtime (time out of service), resulting from damage. Methods for estimating losses and communicating these losses to stakeholders are at the heart of the evolution of performance-based design, and are discussed in more detail later in this Program Plan.

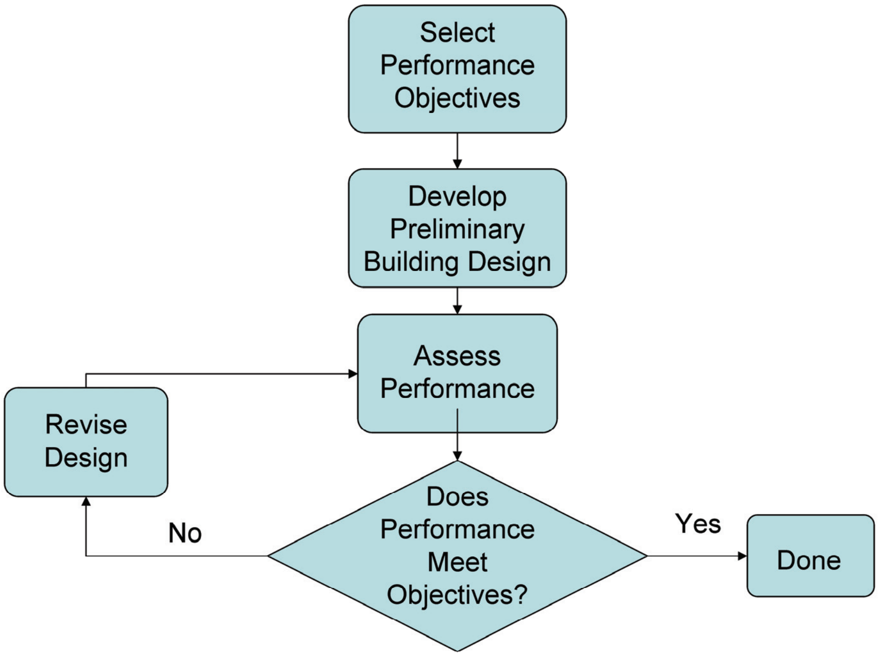


Figure 1-1 Performance-based design flow diagram

Generally, a team of decision makers, including the building owner, design professionals, and building officials, will participate in the selection of performance objectives for a building. This team may consider the needs and desires of a wider group of stakeholders including prospective tenants, lenders, insurers and others who have impact on the value or use of a building, but may not directly participate in the design process.

Stakeholders must evaluate the risk of a hazard event occurring, and must obtain consensus on the acceptable level of performance. The basic questions that should be asked are:

- What events are anticipated?
- What level of loss/damage/casualties is acceptable?
- How often might this happen?

While specific performance objectives can vary for each project, the notion of acceptable performance follows a trend generally corresponding to:

- Little or no damage for small, frequently occurring events
- Moderate damage for medium-size, less frequent events

- Significant damage for very large, very rare events

Once the performance objectives are set, a series of simulations (analyses of building response to loading) are performed to estimate the probable performance of the building under various design scenario events. In the case of extreme loading, as would be imparted by a severe earthquake, simulations may be performed using nonlinear analysis techniques.

If the simulated performance meets or exceeds the performance objectives, the design is complete. If not, the design is revised in an iterative process until the performance objectives are met. In some cases it may not be possible to meet the stated objective at reasonable cost, in which case, some relaxation of the original objectives may be appropriate.

1.4 Advantages of Performance-Based Seismic Design

In contrast to prescriptive design approaches, performance-based design provides a systematic methodology for assessing the performance capability of a building, system or component. It can be used to verify the equivalent performance of alternatives, deliver standard performance at a reduced cost, or confirm higher performance needed for critical facilities.

It also establishes a vocabulary that facilitates meaningful discussion between stakeholders and design professionals on the development and selection of design options. It provides a framework for determining what level of safety and what level of property protection, at what cost, are acceptable to stakeholders based upon the specific needs of a project. Performance-based seismic design can be used to:

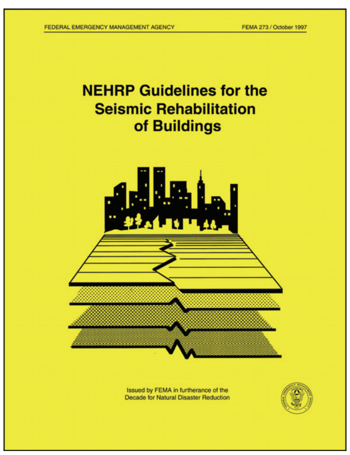
- Design individual buildings with a higher level of confidence that the performance intended by present building codes will be achieved.
- Design individual buildings that are capable of meeting the performance intended by present building codes, but with lower construction costs.
- Design individual buildings to achieve higher performance (and lower potential losses) than intended by present building codes.
- Design individual buildings that fall outside of code-prescribed limits with regard to configuration, materials, and systems to meet the performance intended by present building codes.
- Assess the potential seismic performance of existing structures and estimate potential losses in the event of a seismic event.
- Assess the potential performance of current prescriptive code requirements for new buildings, and serve as the basis for improvements

to code-based seismic design criteria so that future buildings can perform more consistently and reliably.

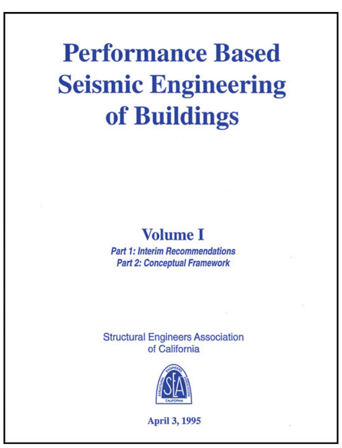
Performance-based seismic design offers society the potential to be both more efficient and effective in the investment of financial resources to avoid future earthquake losses. Further, the technology used to implement performance-based seismic design is transferable, and can be adapted for use in performance-based design for other extreme hazards including fire, wind, flood, snow, blast, and terrorist attack.

1.5 First-Generation Performance-Based Procedures

Performance-based design as a formal process originated in response to the seismic design problem in the 1990's, in which code-based strength and ductility requirements applicable for the design of new buildings could not be practically or reliably applied to the evaluation and upgrade of existing buildings.



Preparation of the initial set of procedures for performance-based seismic design commenced in 1992, as the capstone project in the FEMA program to reduce the seismic hazards of existing buildings. That initial effort culminated with the publication of the FEMA 273 Report, NEHRP *Guidelines for the Seismic Rehabilitation of Buildings* (ATC, 1997a), and its companion document the FEMA 274 NEHRP *Commentary on the Guidelines for the Seismic Rehabilitation of Buildings* (ATC, 1997b), which addressed seismic upgrade of existing buildings. Concurrently, the Structural Engineers Association of California developed the Vision 2000 Report, *Performance-Based Seismic Engineering of Buildings* (SEAOC, 1995), which described a performance-based seismic design framework for design of new buildings. These documents outlined the initial concepts of performance levels related to damageability, and varying levels of hazard.

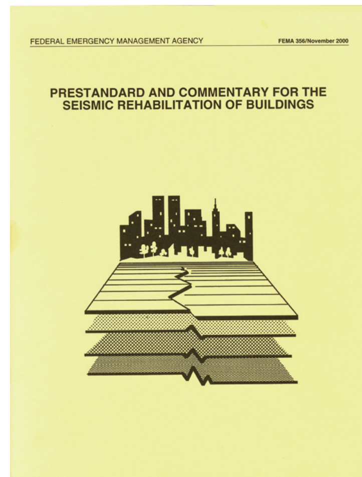


These first-generation procedures introduced the concept of performance in terms of discretely defined performance levels with names intended to connote the expected level of damage: Collapse, Collapse Prevention, Life Safety, Immediate Occupancy, and Operational Performance. They also introduced the concept of performance related to damage of both structural and nonstructural components. Performance Objectives were developed by linking one of these performance levels to a specific level of earthquake hazard.

First-generation procedures also introduced a set of analytical procedures of varying levels of complexity that could be used to simulate the seismic response of buildings, and provided a comprehensive set of guidelines on nonlinear analysis techniques and acceptance criteria. These first-generation procedures represented an important improvement over then-current building code procedures in that they provided a systematic means of designing buildings to achieve a desired level of performance.

1.6 Present Second-Generation Performance-Based Procedures

At present, performance-based seismic design practice is generally based on implementation of procedures and criteria contained within the FEMA 356 *Prestandard and Commentary for the Seismic Rehabilitation of Buildings* (ASCE, 2000). FEMA 356 represents an incremental improvement to the first-generation procedures of FEMA 273. The development of FEMA 356 included technical updates to the analytical requirements and acceptance criteria of FEMA 273 based on information gained from the use of the procedures in engineering practice, and from the FEMA 343 Report, *Case Studies: An Assessment of the NEHRP Guidelines for Seismic Rehabilitation of Buildings* (BSSC, 1999).



With the development of second-generation performance-based procedures, engineering practitioners have become more familiar with its concepts. Performance-based seismic design has become a staple in engineering practice, and the use of advanced nonlinear analysis techniques is becoming more commonplace. Although intended for existing buildings, the procedures are being extrapolated for use in the performance-based design of new buildings.

The expanded use of performance-based procedures in the present second-generation has resulted in a knowledge base of practical experience on designing with performance-based criteria and communicating with stakeholders on performance-based design issues.

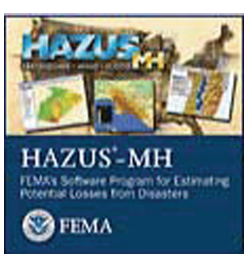
1.7 The Need for Next-Generation Performance-Based Procedures

As the state of knowledge and experience base advances, limitations in second-generation procedures are being identified by researchers and practitioners. These limitations include: (1) questions regarding the accuracy of second-generation analytical procedures in predicting actual building response; (2) questions regarding the level of conservatism present in second-generation acceptance criteria; (3) the inability to reliably and economically apply second-generation performance-based procedures to the design of new buildings; and (4) the need for alternative ways of communicating performance to stakeholders that is more meaningful and useful for decision-making purposes.

In order to fulfill the promise of performance-based engineering and help ensure that performance-based seismic design delivers on its full potential for reducing future losses from earthquakes, next-generation performance-based design procedures are needed to:

- Revise the discrete performance levels defined in first-generation procedures to create new performance measures (e.g. repair costs, casualties, and time of occupancy interruption) that better relate to the decision-making needs of stakeholders, and that communicate these losses in a way that is more meaningful to stakeholders;
- Create procedures for estimating probable repair costs, casualties, and time of occupancy interruption, for both new and existing buildings;
- Expand current nonstructural procedures to explicitly assess the damageability and post-earthquake functionality of nonstructural components and systems, which can constitute a significant percentage of the economic loss associated with damaging earthquakes;
- Develop a framework for performance assessment that properly accounts for, and adequately communicates to stakeholders, limitations in our ability to accurately predict response, and uncertainty in the level of earthquake hazard;
- Refine current analytical techniques to improve our ability to more accurately simulate building response;
- Fill knowledge gaps and investigate the conservatism and reliability of present second-generation acceptance criteria; and
- Modify current structural procedures to assess performance based more on global response parameters, so that the response of individual components does not unnecessarily control the prediction of overall structural performance.

1.8 Framework for Next-Generation Performance-Based Procedures and Relationship to HAZUS



Next-generation performance-based design procedures will be developed using an analytical framework for estimating risk that is well developed and has precedent in a variety of proprietary risk analysis software packages commonly used by the insurance industry and others. The framework will be used to estimate the possibility of incurring earthquake-induced direct losses (repair costs), casualties, and downtime (time of occupancy interruption) for individual buildings of interest, and will address both new buildings and existing buildings. The technical details of the framework for next-generation building-specific loss estimation procedures are described in Appendix A.

Under contract with the FEMA, the National Institute of Building Sciences has implemented a form of this methodology in the Hazards U.S. (HAZUS) loss estimation software. HAZUS was developed primarily for providing policy makers and local planners with the ability to project the potential impacts of earthquakes, hurricanes, and floods on large portfolios of buildings.

HAZUS includes a methodology for developing a performance estimate on a specific building. Known as the HAZUS Advanced Engineering Building Module (AEBM), it enables an experienced engineer with considerable expertise to develop building-specific relationships between earthquake intensity, damage, and loss. These relationships, however, depend on first- and second-generation performance-based analytical techniques for which limitations have been identified and improvement is needed. Also, the method of characterizing the performance of nonstructural components in HAZUS AEBM is very general, and cannot readily account for the various installation details of such components inherent in an individual building design. Therefore, it cannot be used to assist designers in evaluating the potential benefits of design decisions related to improving nonstructural performance.

Together these factors limit the usefulness of HAZUS platform in taking advantage of the benefits of performance-based design. As a result, HAZUS is most applicable to performing global estimates of loss on the general building stock in a region, and is not directly applicable to the performance-based evaluation or design of individual buildings. To the extent that information contained within HAZUS platform can be used for performing individual building assessments, that information will be incorporated within the framework of next-generation performance-based procedures developed under this Program Plan.

Chapter 2

Program Plan: Goals, Background, Organization, and the Performance-Based Design Process

2.1 Program Goals

This Program Plan serves as the basis for a two-phase, multiyear project that will result in next-generation performance-based seismic design guidelines that:

- Are practical, efficient, effective, and applicable to both the upgrade of existing buildings and the design of new buildings;
- Define and use building performance goals that are both measurable and meaningful to building owners and other decision-makers when selecting a basis for design;
- Quantify uncertainty regarding the ability of a building to achieve the desired performance goals;
- Are suitable for practical implementation in a design office; and
- Can be used to improve the provisions of present-day building codes and design procedures.

2.2 Program Background

In September 2001, FEMA contracted with the Applied Technology Council to begin implementation of a plan to develop next-generation performance-based seismic design procedures and guidelines. The preparation of this Program Plan, and developmental work completed to date, has been performed under the ATC-58 project, *Development of Next-Generation Performance-Based Seismic Design Guidelines for New and Existing Buildings*. Work to be performed under this Program Plan updates, refines, and extends the performance based seismic design work of several earlier projects including:

- FEMA 273/274, *NEHRP Guidelines and Commentary for the Seismic Rehabilitation of Buildings* (ATC, 1997a, b).

- FEMA 356, *Prestandard and Commentary* for the *Seismic Rehabilitation of Buildings* (ASCE, 2000), which brought FEMA 273/274 to the prestandard level. The FEMA 356 document is in the process of being replaced by the ASCE 41 *Standard for Seismic Rehabilitation of Existing Buildings* (ASCE, 2006).
- ATC-40, *Seismic Evaluation and Retrofit of Concrete Buildings* (ATC, 1996).
- Vision 2000, *Performance-Based Seismic Engineering of Buildings* (SEAOC, 1995).

This Program Plan updates two earlier FEMA action plans for developing next-generation of performance based seismic design procedures: FEMA 283 *Performance-Based Seismic Design of Buildings – an Action Plan* (EERC, 1996), and FEMA 349 *Action Plan for Performance Based Seismic Design* (EERI, 2000). Both of these earlier plans called for multi-year development programs that would advance the technical aspects of performance-based design, and also address the needs of various stakeholder groups such as building owners, commercial and residential tenants, regulators, lenders, and insurers.

This Program Plan is also intended to implement the developing body of related earthquake engineering research as outlined in *Securing Society Against Catastrophic Earthquake Losses* (EERI, 2002), a national research plan developed by the Earthquake Engineering Research Institute on behalf of the National Science Foundation.

2.3 Preparatory Work from 2001 to Date

Initial work as part of the development of this Program Plan included an evaluation of alternative means of characterizing performance as a basis for design, and a review and update of FEMA 349. The following elements of the FEMA 349 Action Plan have already been conducted in the development of this Program Plan, and have served to help formulate the management structure and technical framework for the development of next-general performance-based seismic design guidelines:

- A project management structure was established in early 2002, including a Project Management Committee to direct the project technical activities, and a Project Steering Committee to provide project oversight and linkage with the research and stakeholder communities**.** The roles and responsibilities of these committees are described in Section 3.3.

- A Workshop on Communicating Earthquake Risk was held in June 2002 and was attended by representatives of several important stakeholder communities including building regulators, mortgage lenders, property insurance professionals, property managers, developers and corporate risk managers, as well as members of the project team. The purpose of the workshop was to confirm that performance-based design would be accepted by the stakeholder communities, identify aspects of earthquake performance of buildings that are of most concern to stakeholders, and determine how best to express building performance in terms that are understandable and useful to stakeholders and decision-makers. The workshop program, activities, findings, and a list of workshop participants have been documented in the ATC-58-1 Report, *Proceedings of FEMA-Sponsored Workshop on Communicating Earthquake Risk*, which can be downloaded from the ATC web site (www.atcouncil.org).
- As part of the effort to make the next-general performance-based seismic design guidelines more understandable and more useful to stakeholders and decision-makers, a Task Group was formed in May 2002 to evaluate alternative methods of expressing and communicating building performance and to develop a report recommending how the project should characterize performance**.** That Task Group participated in the June 2002 workshop, and subsequently developed the ATC-58-2 Report *Preliminary Evaluation of Methods for Defining Performance*, which can be downloaded from the ATC web site (www.atcouncil.org). In addition to summarizing current stakeholder preferences for communicating earthquake risk, this report documents the ways in which performance has been characterized in the past.
- A Performance-Based Design Workshop was held in February 2003 and was attended by prominent members of the structural and earthquake engineering research and practice communities as well as members of the project team. The purpose of this workshop was to obtain information on important advances in performance-based design and input on modifications that should be made to the FEMA 349 Action Plan**.** The workshop program, presentations, discussions, an initial draft of recommended updates to the original FEMA 349 Action Plan, and a list of workshop participants have been documented in the ATC-58-3 Report, *Proceedings of FEMA-Sponsored Workshop on Performance-Based Seismic Design*, which can be downloaded from the ATC web site (www.atcouncil.org).

- A Structural Performance Products (SPP) Team, a Nonstructural Performance Products Team (NPP), and a Risk Management Products (RMP) Team were established in September 2002. These three teams were charged with reviewing FEMA 349, reviewing input received from the workshops, and updating FEMA 349 to serve as the basis for this Program Plan. The roles and responsibilities of these teams are described in Chapters 3 through 6.

As described above, key activities conducted to date by the project have focused on identifying and developing a system that will allow effective communication of earthquake performance choices in ways that are meaningful to stakeholders and decision-makers. No one way of expressing building performance would meet the needs and capabilities of all decision-makers, in part because stakeholders have diverse needs and varying levels of knowledge and experience. However, all decision-makers must understand the risk associated with various options in order to make an intelligent decision. To embrace diverse needs, the Project Management Committee developed a sophisticated and flexible framework for estimating probable earthquake losses in buildings, for either a single scenario event or on a probabilistic basis.

Stakeholders and decision-makers will continue to be involved in the project as work progresses. These activities include ongoing review and input by stakeholder representatives on the Project Steering Committee, periodic input to and reviews by stakeholders on various project products, and a series of efforts that focus on stakeholder needs:

- An effort to identify the key decision-making parameters and processes used by different stakeholder groups.
- Efforts to develop simple tools to assist decision-makers in selecting appropriate performance objectives; and
- Development of guidelines to assist stakeholders in taking advantage of the benefits of performance-based design, including considerations of maintenance.

2.4 Program Organization

This Program Plan is divided into two phases:

- *Phase 1: Developing a Methodology for Assessing the Seismic Performance of Buildings.* In Phase 1, a methodology will be developed for assessing the probable seismic performance of individual buildings in future earthquakes.

- *Phase 2: Developing Performance-Based Seismic Design Procedures and Guidelines.* In Phase 2, seismic design procedures and guidelines will be developed to assist engineers in designing buildings to meet desired performance goals, and to assist stakeholders in taking advantage of the benefits of performance-based design.

Work in each phase will be conducted in six broad categories envisaged in the FEMA 349 Action Plan:

- Planning and Management Program;
- Structural Performance Products;
- Nonstructural Performance Products;
- Risk Management Products;
- Guidelines Products; and
- Stakeholders Guide Products.

The tasks associated with these categories of work are described in Chapters 3 through 6, and summarized briefly below:

Planning and Management Program. The purpose of the Planning and Management Program tasks are to ensure that the project achieves the vision of the plan, and results in products that are accessible and relevant to stakeholders. They include establishing a project management structure, oversight committees, and a formal program to educate stakeholders about performance-based seismic design.

Structural Performance Products. The purpose of the Structural Performance Products tasks are to develop practical and reliable methodologies for assessing the seismic performance of structural systems found in both new and existing buildings, at various seismic hazard levels. These assessment methodologies are intended for use by engineers in designing structures capable of achieving selected performance goals. Recent research results will be incorporated to improve analysis and design procedures and reduce uncertainties in assessing performance.

Nonstructural Performance Products. The Nonstructural Performance Products tasks are similar to the Structural Performance Products tasks, but focus on the nonstructural components of new or existing buildings. Nonstructural components include partitions, ceilings, piping, equipment, contents, and other components and systems attached to the structural framing system. The Nonstructural Performance Products efforts will address both the installation of new components and the protection of components already in place in existing buildings. It will also develop guidelines for component testing and certification.

Risk Management Products. The Risk Management Products tasks are intended to be oriented primarily around financial issues, but also address casualty issues. They include development of methodologies for calculating the costs and benefits of implementing various options under performance-based design. A major effort under this set of tasks includes the development of methods to combine various levels of risk, performance, and hazard to allow a wide range of design objectives to be evaluated as a basis for next-generation procedures. Activities include studies on reliability, cost-benefit modeling, loss reduction, capital planning, and other factors related to risk management. A focus is to provide guidance to stakeholders in selecting appropriate performance objectives.

Guidelines Products. Guidelines Products are the guidelines documents that will be used by engineers and other design professionals in implementing next-generation performance-based seismic design procedures in practice. It is intended that these documents would be published as FEMA guidelines that could be incorporated into future code procedures, if appropriate. These guidelines are envisaged to form the technical basis for everyday design practice, and bring consistency to performance-based seismic design throughout the industry. The guidelines will be usable for both design of new buildings and upgrade of existing buildings, and will include explanatory material (technical commentary, appendices, or supporting documents) to assist in their use. The preparation of Guidelines Products will be performed as part of the Structural Performance Products, Nonstructural Performance Products, and Risk Management Products tasks.

Stakeholders Guide Products. Stakeholders Guide Products are envisaged to function as references and planning tools for owners, institutions with financial interests in the building under consideration, and other non-technical decision-makers. Stakeholders Guide Products will include instruction on the selection of appropriate performance objectives, and financial tools that permit decision-makers to make funding and investment decisions using performance-based design concepts. These guides are to be written for non-technical audiences and will contain graphical aids and example applications. The preparation of Stakeholders Guide Products will be performed as part of the Structural Performance Products, Nonstructural Performance Products, and Risk Management Products tasks.

2.5 Performance-Based Seismic Design Process

This section provides an expanded discussion of the performance-based seismic design process introduced in Section 1.3, as it relates to next-generation performance-based design procedures envisioned by this Program Plan.

As described earlier, performance-based design is an iterative process that begins with the selection of performance objectives, followed by the development of a preliminary design, an assessment as to whether or not the design meets the performance objectives, and finally redesign and reassessment, if required, until the desired performance level is achieved. Each of these steps is described in the sections that follow. Figure 2-1 shows how Phases 1 and 2 of this Program Plan will contribute to the steps in the overall process. A more detailed description of the technical framework for the next-generation seismic performance assessment methodology is provided in Appendix A.

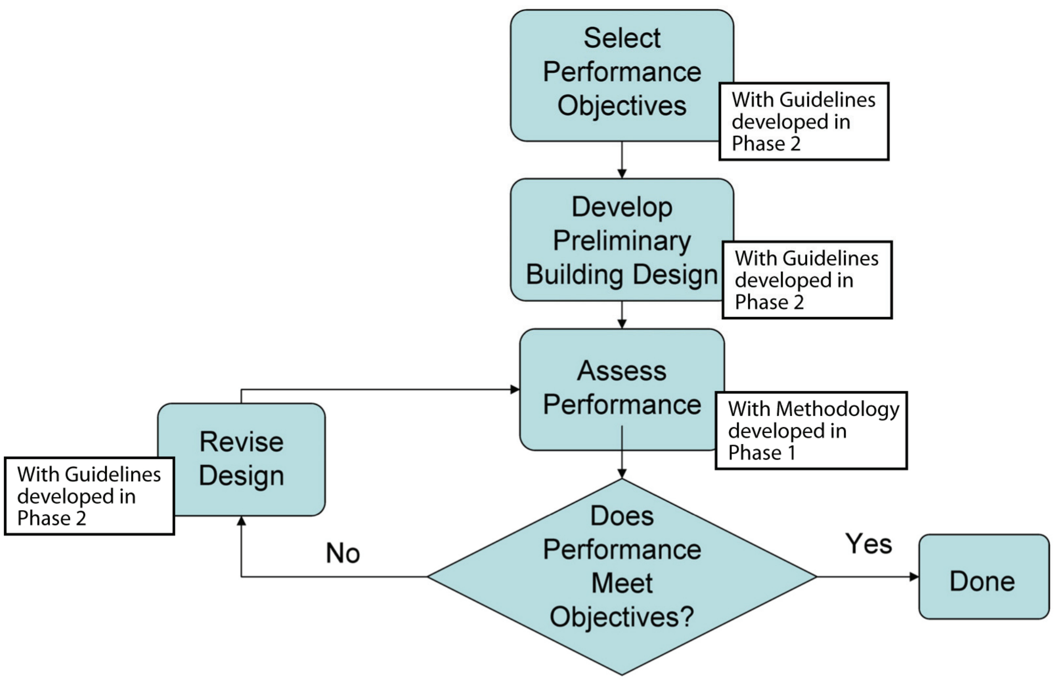


Figure 2-1 Performance-based design process as it relates to Phase 1 and Phase 2 of the Program Plan.

2.5.1 Step 1: Select Performance Objectives

The process begins with the selection of design criteria stated in the form of one or more performance objectives. Performance objectives are statements of the acceptable risk of incurring different levels of damage and the consequential losses that occur as a result of this damage, at a specified level of seismic hazard. Since losses can be associated with structural damage, nonstructural damage, or both, performance objectives must be expressed considering the potential performance of both structural and nonstructural systems.

In the next-generation performance-based design procedures, performance objectives are statements of the acceptable risk of incurring casualties, direct economic loss (repair costs), and occupancy interruption time (downtime) associated with repair or replacement of damaged structural and nonstructural building elements, at a specified level of seismic hazard. These performance objectives can be stated in three different risk formats:

An *intensity-based performance objective* is a quantification of the acceptable level of loss, given that a specific intensity of ground shaking is experienced. An example of an *intensity-based performance objective* is a statement that if ground shaking with a 475-year-mean-recurrence intensity occurs, repair cost should not exceed 20 percent of the building's replacement value, there should be no life loss or significant injury, and occupancy interruption should not exceed 30 days.

A *scenario-based performance objective* is a quantification of the acceptable level of loss, given that a specific earthquake event occurs. An example of a scenario-based performance objective is a statement that if a magnitude-7.0 earthquake occurs on the San Andreas fault, repair costs should not exceed 5% of the building replacement cost, there should be no life loss or significant injury, and occupancy of the building should not be interrupted for more than a week.

A *time-based performance objective* is a quantification of the acceptable probability over a period of time that a given level of loss will be experienced or exceeded, considering all of the earthquakes that might affect the building in that time period and the probability of occurrence of each. An example of a time-based performance objective is a statement that there should be less than a 2 percent chance in 50 years that life loss will occur in the building due to earthquake damage, on the average the annual earthquake damage repair costs for the building should not exceed 1% of the replacement cost, and the mean return period for occupancy interruption exceeding one day should be 100 years.

Phase 2 of this Program Plan includes the development of guides to assist stakeholders in selecting appropriate performance objectives, and taking advantage of the benefits of performance-based design.

2.5.2 Step 2: Develop Preliminary Building Design

The preliminary design for a structure includes definition of a number of important building attributes that can significantly affect the performance capability of the building. These attributes include:

- Location and nature of the site.
- Building configuration, including the number of stories, story height, floor plate arrangement at each story, and the presence of irregularities.
- Basic structural system, for example, steel moment frame or masonry bearing walls.
- Presence of any protective technologies, for example, seismic isolators, energy dissipation devices, or damage-resistant elements.
- Approximate size and location of various structural and nonstructural components and systems, and specification of the manner in which they are installed.

Selection of an appropriate preliminary design concept is important for effectively and efficiently implementing the performance-based design process. Inappropriate preliminary designs could result in extensive iteration before an acceptable solution is found, or could result in solutions that do not efficiently meet the performance objectives.

At present, engineers have few resources on which to base a preliminary design for meeting a specified performance objective. Some may refer to current building code provisions, others might refer to first-generation performance-based design procedures, and still others might use a more intuitive approach.

Phase 2 of this Program Plan includes the development of guides to assist engineers in identifying appropriate strategies for design and developing efficient preliminary designs.

2.5.3 Step 3: Assess Performance

After the preliminary design has been developed, a series of simulations (analyses of building response to loading) are performed to assess the probable performance of the building. Performance assessment includes the following steps:

- Characterization of the ground shaking hazard.
- Analysis of the structure to determine its probable response and the intensity of shaking transmitted to supported nonstructural components

as a function of ground shaking intensity. In the case of extreme loading, as would be imparted by a severe earthquake, simulations may be performed using nonlinear analysis techniques.

- Determination of the probable damage to the structure at various levels of response.
- Determination of the probable damage to nonstructural components as a function of structural and nonstructural response.
- Determination of the potential for casualty, capital and occupancy losses as a function of structural and nonstructural damage.
- Computation of the expected future losses as a function of intensity, structural and nonstructural response, and related damage.

Performance assessment is based on assumptions of a number of highly uncertain factors. These factors include:

- Quality of building construction and building condition at the time of the earthquake.
- Actual strength of the various materials, members, and their connections incorporated in the building.
- Nature of building occupancy at the time of the earthquake, the types of tenant improvements that will be present, how sensitive these tenant improvements might be to the effects of ground shaking, and the tolerance of the occupancy to operating in less than ideal conditions.
- Availability of designers and contractors to conduct repairs following the earthquake.
- Owner's efficiency in obtaining the necessary assistance to assess and repair damage.

To complete a performance assessment, statistical relationships between earthquake hazard, building response, damage, and then loss are required. In a general sense, the process involves the formation of four types of probability functions, respectively termed: hazard functions, response functions, damage functions, and loss functions, and mathematically manipulating these functions to assess probable losses.

Hazard functions are mathematical expressions of the probability that a building will experience ground shaking of different intensity levels, where intensity may be expressed in terms of peak ground acceleration, spectral response acceleration or similar parameters. Hazard functions can be derived from the U.S. Geological Survey (USGS) ground shaking hazard maps, or may be developed based on a site-specific study that considers the seismicity of various faults in the region and the response characteristics of the building site.

Response functions are mathematical expressions of the conditional probability of incurring various levels of building response, given that different levels of ground shaking intensity are experienced. Building response is expressed in the form of parameters that are obtained from structural analysis, including story drifts, member forces, joint plastic rotation demands, floor accelerations and similar parameters. They are obtained by performing structural analysis of a building for different intensities of ground shaking.

Damage functions are mathematical expressions of the conditional probability that the building as a whole, or individual structural and nonstructural components, will be damaged to different levels, given that different levels of building response occur. Damage functions are generally established by laboratory testing, analytical simulation or a combination of these approaches.

Loss functions are mathematical expressions of the conditional probability of incurring various losses, including casualties, repair and replacement costs, and occupancy interruption times, given that certain damage occurs. They are determined by postulating that different levels of building damage have occurred and estimating the potential for injury persons who may be present as well as the probable repair /restoration effort involved.

The mathematical manipulation of these functions may take on several different forms. For some types of performance assessments, closed-form solutions can be developed that will enable direct calculation of loss. For other types of assessment, it may be necessary to perform either numerical integration or Monte Carlo type analyses. Appendices B and C provide more detailed technical information on these alternative computations of loss.

2.5.4 Step 4: Revise Design

If the simulated performance meets or exceeds the performance objectives, the design is completed. If not, the design must be revised in an iterative process until the performance objectives are met.

The design guides, to be developed in Phase 2 of this Program Plan, for assisting engineers in identifying appropriate strategies for design and for developing efficient preliminary designs are intended to serve as resources for efficient redesign to meet performance objectives. In some instances it may not be possible to meet the stated objectives at reasonable cost, in which case, some relaxation of the original performance objectives may be appropriate.

2.6 Applicability of Performance-Based Design to Other Structural Hazards

Design professional and stakeholder communities are also interested in the development of performance-based design procedures and guidelines for other extreme hazards including fire, wind, flood, snow, blast, and progressive collapse due to blast or explosion.

There is substantial past precedent to indicate that practice improvements in performance-based design for seismic resistance have direct impact and applicability to performance-based design for other hazards. For example, the performance-based design options contained both in the *International Performance Code* (ICC, 2001) and *NFPA-5000 Building and Construction Safety Code* (NFPA, 2003), which are applicable to the full range of design perils, are patterned after the performance basis developed for FEMA 356 (ASCE, 2000). The *GSA Progressive Collapse Guidelines* (ARA, 2003) used in the design of federal buildings to resist terror-related blast hazards are also based on technology contained in the FEMA 356 *Prestandard* as well as the FEMA 350 *Recommended Seismic Design Criteria for New Steel Moment-Frame Buildings* (SAC, 2000a), a publication on performance-based seismic design of steel moment frame structures.

The basic methodology developed under this program does not presently address design for other hazards directly; however, the technological framework and procedures are transferable, and with modification, could be applicable to performance-based design for other hazards. While this Program Plan does not explicitly include development of design guidance for other hazards, measures will be taken to ensure coordination of the development of performance-based seismic design guidelines with other parallel efforts. Relevant material for other hazards will be referenced or incorporated into project publications, where applicable. These activities will be carried out on an ongoing basis by the Project Management Committee, the Project Steering Committee, and other members of the project team.

Chapter 3

Phase 1: Developing a Methodology for Assessing the Seismic Performance of Buildings

3.1 Phase 1 Objectives

Phase 1 of this Program Plan, *Developing a Methodology for Assessing the Seismic Performance of Buildings*, will develop a methodology for assessing the probable performance of individual buildings in future earthquakes. Work preparatory to beginning Phase 1 has already been performed, and the Program Plan can be initiated immediately.

Phase 1 will update and refine the existing framework for performance assessment available in present-generation performance-based procedures, create a practical methodology to assess the consequences of performance (losses) considering the unique design and construction characteristics of individual buildings, and establish new vocabulary for communicating performance to stakeholders in the form of losses related to casualties, direct economic loss (repair costs), and occupancy interruption time (downtime).

3.1.1 Expandable Framework

The performance assessment methodology developed in Phase 1 will be applicable to all classes of buildings and structural and nonstructural systems commonly used in buildings. Research data does not currently exist, however, to fill in all the necessary data to complete damage and loss calculations for all such structural and nonstructural systems. The framework for performance assessment depicted in the guidelines developed in Phase 1 will clearly identify where such data exists and where it does not. "Space" will be left in the new framework so that new information can be "filled in" by future research efforts on specific types of structural and nonstructural systems. Where research data does not exist, this framework will provide direction on how new data should be developed. Phase 1 of this Program Plan has been developed based on the following information:

1. *Complete framework.* A complete framework for implementing performance assessment procedures will be developed, including procedures for developing response, damage, and loss functions for a building of any construction and occupancy. The framework will include information for selected structural and nonstructural systems, for

which research data exist. Procedures on how new structural and nonstructural performance data should be developed and incorporated into the methodology will be provided in the project report *Interim Protocols For Determining Seismic Performance Characteristics of Structural and Nonstructural Components Through Laboratory Testing* (FEMA 461, under development).

2. *Structural Systems.* Standard structural response, damage, and loss functions will be developed for structural systems for which sufficient research data presently exist. These systems are identified in Chapter 4. Procedures for modifying these functions to suit specific building designs will also be developed, so that the methodology can be implemented by engineers. The framework will clearly identify where such data exists and where it does not, and will allow for future expansion to include new research as it is developed.

3. *Nonstructural Components and Systems.* Standard nonstructural response, damage, and loss functions will be developed for nonstructural systems commonly used in buildings. Sufficient earthquake performance data for some classes of nonstructural components and systems has been developed in support of seismic qualification efforts by the U.S. Nuclear Regulatory Commission, the Department of Energy, and private industry sources. Efforts will be made to collect these data and obtain permission for their use. Procedures for developing the response, damage, and loss functions from such data will be developed and documented. For nonstructural components and systems for which no such data presently exist, engineering judgment will be used to establish notional response, damage, and loss functions so that complete performance assessments can be performed.

3.1.2 Research Needed From Other Programs

To complete the development of a performance assessment methodology that addresses all structural and nonstructural systems commonly used in buildings, basic research is needed on simulation techniques, structural and nonstructural component testing, and ground motion hazard characterization. This Program Plan, however, utilizes basic research that has already been performed, and assumes that the necessary basic research will be performed by other programs: the Network for Earthquake Engineering Simulation (NEES) program currently being conducted under National Science Foundation sponsorship; the Advanced National Seismic System (ANSS), currently being constructed by the U.S. Geologic Survey; the programs of the three NSF-funded national earthquake engineering research centers; and other university-based research programs.

It is reasonable to expect that private industry, including the various construction materials trade associations and individual construction product manufacturers and suppliers, will also perform some of the research necessary to facilitate the use of their products and materials in a performance-based design environment.

3.2 Phase 1 Organization

Phase 1 of the Program Plan is organized around six broad categories of work introduced in Section 2.4: Planning and Management Program; Structural Performance Products; Nonstructural Performance Products; Risk Management Products; Guidelines Products; and Stakeholders Guide Products.

Phase 1 work has been subdivided into one overall coordinating and management function and three technical areas. Work in each technical area will be performed by one of three Product Development Teams, consisting of dedicated engineers and researchers with specialized expertise structural performance, nonstructural performance, or risk management.

3.3 Phase 1 Project Management

Planning and Management Program tasks will be carried out within the project management structure shown in Figure 3-1. It is envisaged that this management structure will be used throughout implementation of both Phase 1 and Phase 2 of the program. The project management structure consists of three committees:

- Project Management Committee
- Project Technical Committee
- Project Steering Committee

Collectively, these committees provide management, technical oversight, and control of the work performed by the three Product Development Teams. They are in place to ensure that results are coordinated between the teams and consistent with the overall goals of the Program Plan.

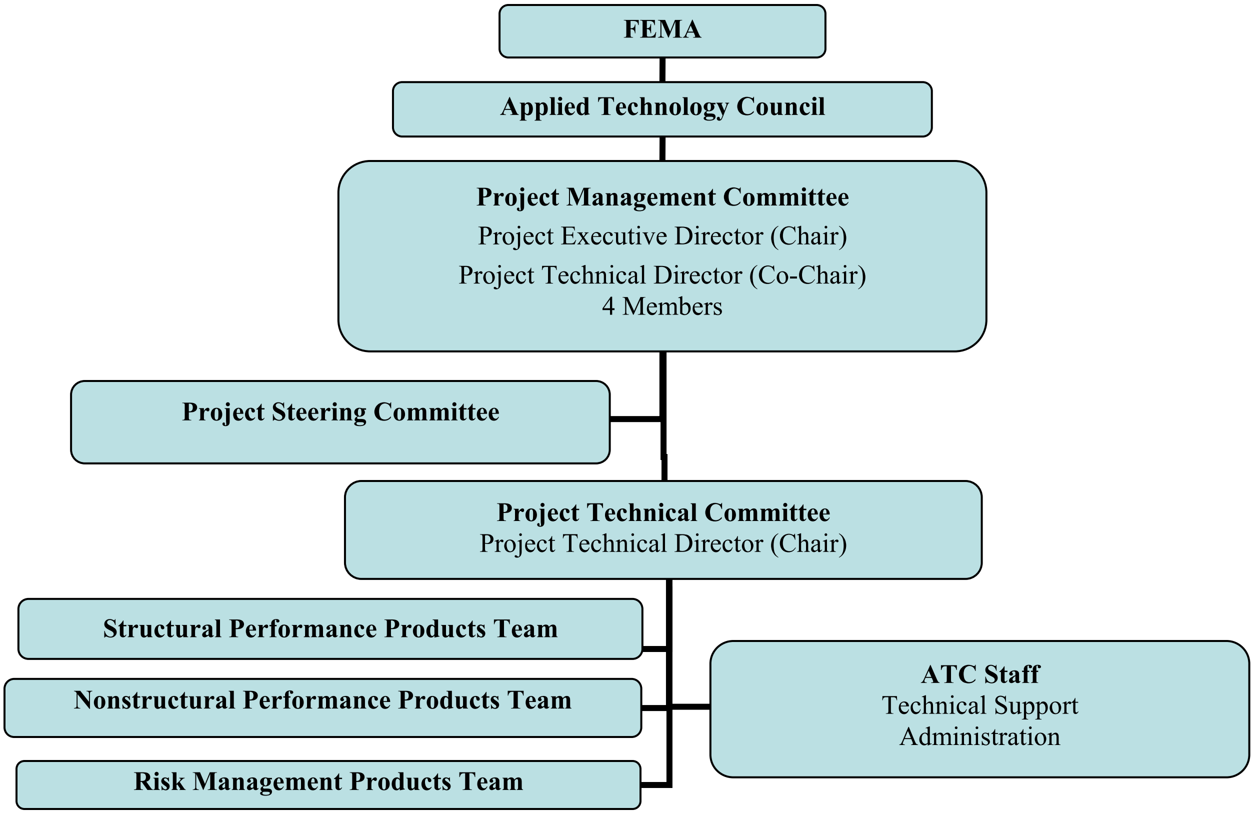


Figure 3-1 Project management structure.

3.3.1 Project Management Committee

The Project Management Committee will review Program activities on a regular basis and will be available for immediate consultation by the funding agency and by all three Product Development Teams, as required. The Project Management Committee will select consultants and form teams to carry out program tasks, including product development and review. These consultants will be qualified academic researchers, engineering practitioners, and/or other personnel qualified to perform the specific functions needed. The Project Management Committee will be responsible for defining the scope of work for consultants and project teams, and for ensuring that work performed by each consultant or team is timely, accurate, and useful. The Project Management Committee will:

- Develop status report formats for each consultant or team to use on a regular basis.
- Act as liaison with other related concurrent research and development projects.
- Hold regular meetings to discuss progress of the project and resolve any conflicts.

- Serve as a conduit for transfer of information between consultants and teams to ensure that all efforts are complimentary and supplementary.

The Project Management Committee will consist of six people, including a Project Executive Director, who will serve as chair and be responsible for the management of the project financial performance; the Project Technical Director, who will serve as co-chair and be responsible for technical direction of project efforts; and four senior representatives, one from each of the following communities: engineering research, structural design, building regulation, and social science research. The Project Management Committee will meet at approximately 6-8 week intervals throughout the project.

3.3.2 Project Technical Committee

The Project Technical Committee will coordinate the efforts of the three Product Development Teams. It will be composed of the Project Executive Director, Project Technical Director, other selected members of the Project Management Committee, and team leaders for each of the three Product Development Teams. The committee will be chaired by the Project Technical Director.

The Project Technical Committee will generally meet on a quarterly basis throughout the duration of the program. Some of these meetings will involve additional representatives of the three Development Teams so that specific technical issues may be presented and discussed and technical interfaces developed and resolved.

3.3.3 Project Steering Committee

The Project Steering Committee will serve as an advisory body to the Project Management Committee and will be populated to provide diverse perspectives on key technical issues and conduct of the project. The Project Steering Committee will make recommendations on products to be developed, project personnel, timetables for different tasks, and will provide technical and content review of products.

The Project Steering Committee will be composed of 12 to 14 senior representatives of various stakeholder communities, including design professionals, researchers, building developers, building regulators, building owners, lenders, insurers, and other groups. The exact size and composition of this group may change over time, as best suits the needs of the program and the technical work that is currently being performed. The Project Steering Committee will generally meet one or more times per year.

3.4 Summary of Phase 1 Technical Tasks

Work in each technical area will be performed by one of three Product Development Teams:

- **Structural Performance Products Team.** Tasks related to assessing the performance of structural systems including development of response, damage (fragility), and loss functions for various structural systems.
- **Nonstructural Performance Product Team.** Tasks related to assessing the performance of nonstructural components and systems including development of response, damage (fragility), and loss functions for these components and systems.
- **Risk Management Product Team.** Tasks related to integrating the structural and nonstructural performance functions with the ground shaking hazard to obtain estimates of performance in terms of probable casualties, probable repair and replacement costs, and probable loss of occupancy and use of buildings, as well as development of the means for communicating these risks to stakeholders and decision-makers.

A summary of Phase 1 tasks to be performed by each of these teams is provided in the subsections that follow. Detail descriptions of Phase 1 tasks are provided in Chapter 4.

3.4.1 Structural Performance Products Tasks

Principal Phase 1 tasks to be performed by the Structural Performance Products (SPP) Team will include:

- SPP-1: Prepare structural sections of the Performance Assessment Guidelines including guidance on selection of ground motions, performing structural analysis, development of response functions and damage functions.
- SPP-2: Identify appropriate structural response quantities (engineering demand parameters) for use in predicting damage to the different types of structural components and systems.
- SPP-3: Identify appropriate measures of ground shaking intensity, such as spectral response acceleration at the structure's fundamental period, and appropriate methods of selecting and scaling ground motion records to represent various shaking intensities.
- SPP-4: Develop rules for modeling and analyzing structures at various intensities of shaking, and considering variability in strength, stiffness and damping, to derive structure-specific response functions.

- SPP-5: Determine appropriate damage states for individual structural components, and entire structural systems that are sufficient to permit estimation of casualties, repair/replacement costs and downtime.
- SPP-6: Develop structural designs for a series of case study buildings that will be used as a basis for development and testing of the performance assessment methodology and which will be used as example applications in the guidelines.
- SPP-7: Develop analytical procedures that can be used to predict the demands on nonstructural components and systems as a function of ground shaking intensity.
- SPP-8: Develop general procedures that can be used to construct loss functions that relate the probability of experiencing various amounts of casualties, repair/replacement costs and downtime, as a function of structural damage states, and develop default relationships for typical structural systems.

3.4.2 Nonstructural Performance Products Tasks

Principal Phase 1 tasks to be performed by the Nonstructural Performance Products (NPP) Team will include:

- NPP-1: Prepare nonstructural sections of the Performance Assessment Guidelines including guidance on determining the damageability of nonstructural components and systems, determining the behavior of these components at varying levels of building response, and predicting the consequences of damage to these components with regard to casualties, repair costs and downtime.
- NPP-2: Develop a taxonomy of the typical nonstructural components and systems found in buildings, identifying those which are damageable and which have significant potential consequences in terms of casualties, repair/replacement cost and downtime.
- NPP-3: Identify meaningful damage descriptors for the various types of nonstructural components and systems that are useful for determining the potential for incurring earthquake induced losses.
- NPP-4: Identify appropriate characterizations of the shaking input to various types of nonstructural components and systems that best correlate with damage to these components and systems.
- NPP-5: Identify and obtain access to the various proprietary and public domain databases of information on the seismic damageability of various types of nonstructural components.

- NPP-6: Develop standard procedures to perform laboratory tests of nonstructural components as a means of developing damage functions for these components.
- NPP-7: Develop approximate, simplified procedures to estimate response parameters for nonstructural components for a given set of engineering demand parameters.
- NPP-8: Develop approximate analytical procedures that can be used to predict damage sustained by complex nonstructural systems.
- NPP-9: Develop general procedures that can be used to construct loss functions that relate the probability of experiencing various amounts of casualties, repair/replacement costs and downtime, as a function of nonstructural damage states for various types of components and systems, and develop default relationships for typical components and systems.
- NPP-10: Develop specifications of nonstructural components and systems for the series of case study buildings that will be used as a basis for development and testing of the performance assessment methodology and which will be used as example applications in the guidelines.

3.4.3 Risk Management Products Tasks

Principal Phase 1 tasks to be performed by the Risk Management Products (RMP) Team will include:

- RMP-1: Prepare sections of the Performance Assessment Guidelines relating to the basic performance assessment methodology, including methods for expressing seismic performance of buildings, developing loss functions and integrating and aggregating losses to produce various types of probable casualty, repair/replacement cost and downtime assessments.
- RMP-2: Develop general procedures for determining structural loss functions that relate probable casualties, repair/replacement costs and downtime to various types of structural damage.
- RMP-3: Develop general procedures for determining nonstructural loss functions that relate probable casualties, repair/replacement costs and downtime to various types of nonstructural damage.
- RMP-4: Develop a basic mathematical approach for calculating probable casualties, repair/replacement costs and downtime, as a function of ground shaking hazard, structural and nonstructural response and damage.

- RMP-5: Synthesize the basic mathematical approach for calculating probable performance into a systematic procedure that can be applied to real buildings in the design office.
- RMP-6: Develop a practical approach that can be used to sum the effects of damage to the collection of individual structural and nonstructural components that comprise a building, into a coherent estimate of probable loss to the building, considering the interaction and dependencies involved.
- RMP-7: Develop practical procedures to calculate loss as a function of the predicted damage to various elements.
- RMP-8: Work with representatives of various stakeholder groups including building developers, owners, investors, tenants, regulators, lenders, insurers and design professionals to develop a common means of communicating seismic performance of buildings that is useful to the process of selecting appropriate or desired building performance as a basis for design projects.
- RMP-9: Develop standard methods of characterizing building performance that meet the need of the various stakeholders.

3.5 Phase 1 Projected Program Costs and Schedule

Phase 1 of this Program Plan was originally intended to be accomplished in five years, contingent on the availability of sufficient levels of funding to enable the necessary work to be performed in the planned sequence. Figure 3-2 presents an overall summary of tasks and schedule for the originally planned Phase 1 work. Detailed descriptions of Phase 1 tasks are provided in Chapter 4.

The original Phase 1 total projected project costs were estimated at approximately $11 million in 2004 dollars. Estimates of personnel and other costs associated with the Phase 1 tasks of this Program Plan have been developed using prevailing labor costs common to projects of this type at the time this plan was prepared, and do not include escalation due to changes in the value of money, labor rates, internal government costs, or inflation. Table 3-1 presents an overall picture of the Phase 1 program as originally developed, broken down by Product Development Area. Table 3-2 presents a detailed breakdown of these original costs by task, and shows how these costs were intended to have been distributed throughout the program.

Table 3-3 and Table 3-4 present an overall picture of the Phase 1 reduced-scope program prepared at the request of FEMA. The budget for the reduce-scope program is approximately 50% of that for the original program, and the project schedule has been extended to seven years. Table 3-3 presents the Phase 1 reduced-scope program broken down by Product Development Area, and Table 3-4 presents a detailed breakdown of reduced-scope costs by specific tasks. The project is currently working at a reduced funding level, and Phase 1 development efforts are in year four of the extended seven year schedule.

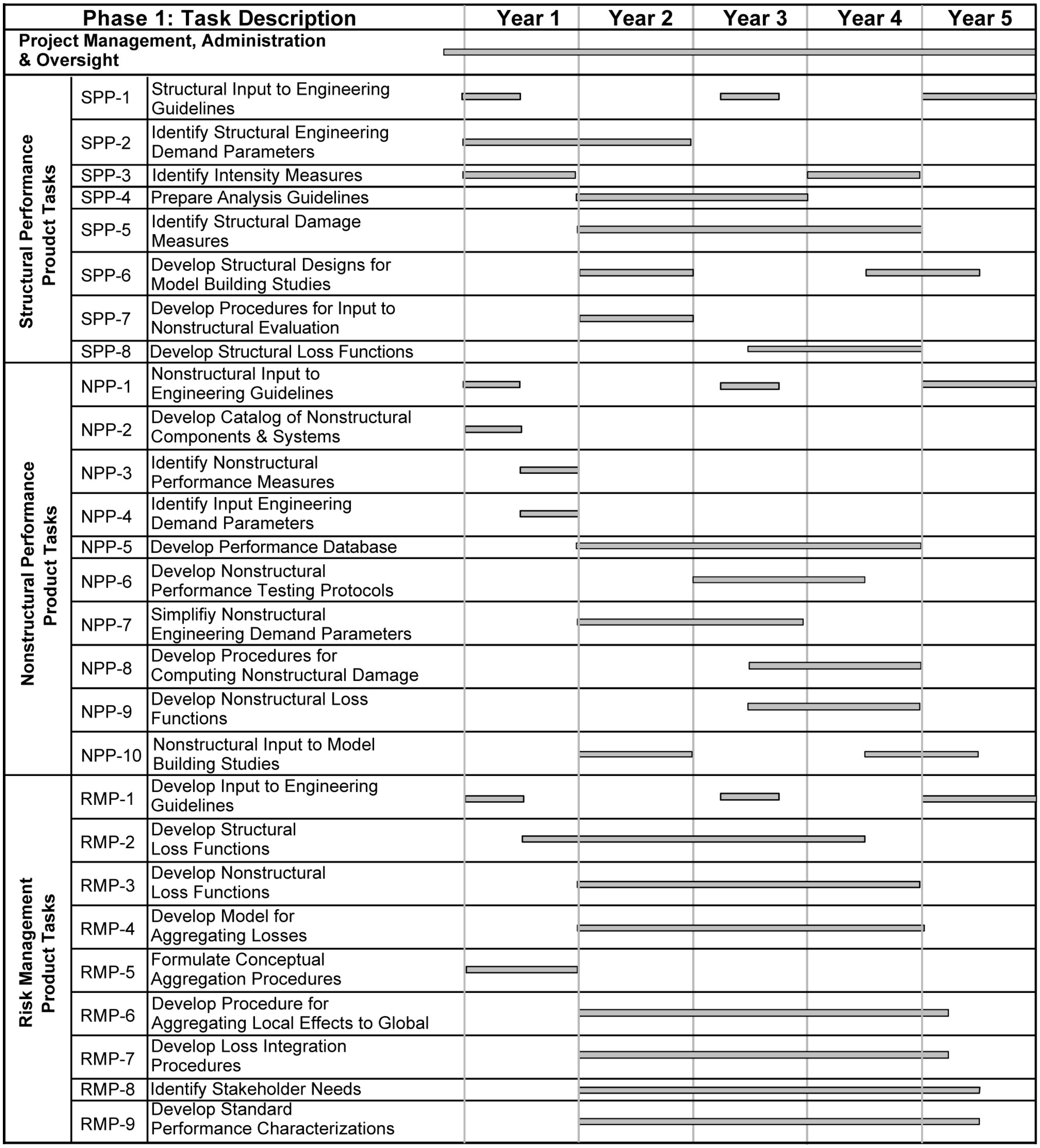


Figure 3-2 Summary of tasks and schedule for Phase 1: *Developing a Methodology for Assessing the Seismic Performance of Buildings*.

Table 3-1 Original Projected Costs by Product Development Area, Phase 1: Development of Performance Assessment Guidelines

Product Development Area/Cost Element	Cost ($1,000)
Structural Performance Products	$2,545
Nonstructural Performance Products	2,450
Risk Management Products	3,080
Project Management, Administration, Oversight (Review), and Other Costs (Travel, Communications, Supplies and Equipment)	3,375
Project Total	**$11,450**

Table 3-2 Original Projected Program Costs by Task and Year ($1,000); Phase 1

Task	Year 1	Year 2	Year 3	Year 4	Year 5	Total
SPP-1 Structural Input to Performance Assessment Guidelines	$110	-	$110	-	$320	*540*
SPP-2 Identify Structural Engineering Demand Parameters (EDPs)	130	130	-	-	-	*260*
SPP-3 Identify Intensity Measures	110	-	-	110	-	*220*
SPP-4 Prepare Analysis Guidelines	-	175	175	-	-	*350*
SPP-5 Identify Structure Damage Measures	-	170	170	150	-	*490*
SPP-6 Structural Input to Model Building Studies	-	150	-	180	180	*510*
SPP-7 Develop Procedures for Input to Nonstructural Evaluation	-	75	-	-	-	*75*
SPP-8 Develop Structural Loss Functions	-	-	50	50	-	*100*
SPP Total	**350**	**700**	**505**	**490**	**500**	***2545***
NPP-1 Nonstructural Input to Performance Assessment Guidelines	100	-	100	-	290	*490*
NPP-2 Develop Catalog of Nonstructural Components and Systems	150	-	-	-	-	*150*
NPP-3 Identify Nonstructural Performance Measures	150	-	-	-	-	*150*
NPP-4 Identify Input EDPs for Nonstructural Components	75	-	-	-	-	*75*
NPP-5 Develop Nonstructural Performance Database	-	170	170	130	-	*470*
NPP-6 Develop Nonstructural Performance Evaluation Protocols	-	-	185	90	-	*275*
NPP-7 Simplify Nonstructural EDPs	-	195	195	0	-	*390*
NPP-8 Develop Procedures for Computing Nonstructural Damage	-	-	75	155	-	*230*
NPP-9 Develop Nonstructural Loss Functions	-	-	35	35	-	*70*
NPP-10 Nonstructural Input to Model Building Studies	-	50	-	50	50	*150*
NPP Total	**475**	**415**	**760**	**460**	**340**	***2450***
RMP-1 Develop Input to Performance Assessment Guidelines	100	-	100	-	290	*490*
RMP-2 Develop Structural Loss Functions	85	170	170	85	-	*510*
RMP-3 Develop Nonstructural Loss Functions	-	170	170	170	-	*510*
RMP-4 Develop Model for Aggregating Losses	-	55	110	70	60	*295*
RMP-5 Formulate Concept Aggregation Procedures	135	-	-	-	-	*135*
RMP-6 Procedure for Aggregating Local Effects to Global	-	85	110	110	40	*345*
RMP-7 Develop Loss Integration Procedures	-	35	30	40	30	*135*
RMP-8 Identify Stakeholder Needs	-	65	100	100	85	*350*
RMP-9 Develop Standard Performance Characterizations	-	45	100	100	65	*310*
RMP Total	**320**	**625**	**890**	**675**	**570**	***3080***
Project Management, Oversight & Administration	475	475	475	475	475	*2375*
Other Direct Costs	200	200	200	200	200	*1000*
Annual Totals	**$1,820**	**$2,415**	**$2,830**	**$2,300**	**$2,085**	***$11,450***

Table 3-3 Reduced-Scope Projected Costs by Product Development Area, Phase 1: Development of Performance Assessment Guidelines

Product Development Area/Cost Element	Cost ($1,000)
Structural Performance Products	$785
Nonstructural Performance Products	786
Risk Management Products	965
Project Management, Administration, Oversight (Review), and Other Costs (Travel, Communications, Supplies and Equipment)	2462
Project Total	**$4998**

Table 3-4 Reduced-Scope Projected Program Costs by Task and Year ($1,000); Phase 1

Task	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Total
SPP-1 Structural Input to Performance Assessment Guidelines	$8	-	$33	-	$42	$42	$33	*158*
SPP-2 Identify Structural Engr. Demand Parameters)	-	20	20	-	-	-	-	*40*
SPP-3 Identify Intensity Measures	-	20	10	-	-	-	-	*30*
SPP-4 Prepare Analysis Guidelines	-	10	30	75	-	-	-	*115*
SPP-5 Identify Structure Damage Measures	70	70	20	-	-	-	-	*160*
SPP-6 Structural Input to Model Building Studies	17	33	-	17	33	33	-	*133*
SPP-7 Dev. Procedures for Input to Nonstructural Evaluation	-	-	-	50	-	-	-	*50*
SPP-8 Develop Structural Loss Functions	-	33	33	33	-	-	-	*99*
SPP Total	**95**	**186**	**146**	**175**	**75**	**75**	**33**	***785***
NPP-1 Nonstr. Input to Performance Assessment Guidelines	8	-	33	-	42	42	33	*158*
NPP-2 Develop Catalog of Nonstructural Components	20	-	-	-	-	-	-	*20*
NPP-3 Identify Nonstructural Performance Measures	-	65	-	-	-	-	-	*65*
NPP-4 Identify Input EDPs for Nonstructural Components	15	30	-	-	-	-	-	*45*
NPP-5 Develop Nonstructural Performance Database	-	-	50	40	-	-	-	*90*
NPP-6 Dev. Nonstructural Performance Evaluation Protocols	20	-	-	-	-	-	-	*20*
NPP-7 Simplify Nonstructural EDPs	10	10	-	-	-	-	-	*20*
NPP-8 Develop Procedures for Computing Nonstr. Damage	-	-	65	45	85	-	-	*195*
NPP-9 Develop Nonstructural Loss Functions	-	-	10	10	10	10	-	*40*
NPP-10 Nonstructural Input to Model Building Studies	17	33	-	17	33	33	-	*133*
NPP Total	**90**	**138**	**158**	**112**	**170**	**85**	**33**	***786***
RMP-1 Develop Input to Performance Assessment Guidelines	8	-	33	-	42	42	33	*158*
RMP-2 Develop Structural Loss Functions	5	10	-	-	-	-	-	*15*
RMP-3 Develop Nonstructural Loss Functions	10	20	55	45	45	40	-	*215*
RMP-4 Develop Model for Aggregating Losses	-	-	-	17	33	33	-	*83*
RMP-5 Formulate Concept Aggregation Procedures	17	33	-	-	-	-	-	*50*
RMP-6 Proc. for Aggregating Local Effects to Global	-	39	40	40	-	-	-	*119*
RMP-7 Develop Loss Integration Procedures	-	-	20	75	75	100	-	*270*
RMP-8 Identify Stakeholder Needs	-	15	20	-	-	-	-	*35*
RMP-9 Develop Standard Performance Characterizations	-	10	10	-	-	-	-	*20*
RMP Total	**40**	**127**	**178**	**177**	**195**	**215**	**33**	***965***
Project Management, Oversight & Administration	255	240	230	230	230	240	120	*1545*
Other Direct Costs	120	58	137	157	180	135	130	*917*
Annual Totals	**$600**	**$749**	**$849**	**$851**	**$850**	**$750**	**$349**	***$4998***

Chapter 4

Phase 1: Developing a Methodology for Assessing the Seismic Performance of Buildings—Technical Tasks

4.1 Phase 1 Structural Performance Products Tasks

The purpose of the Structural Performance Products tasks is to develop a practical and reliable generalized methodology for assessing the performance of building structural systems, including: identification of appropriate intensity measures for use in analysis; identification of preferred approaches to employing structural analysis to predict building response as a function of intensity; and methods of predicting structural damage as a function of building response. The Structural Performance Products tasks will be performed in coordination with the Risk Management Product tasks related to calculating losses as a function of structural and nonstructural damage, and the Nonstructural Performance Products tasks that predict nonstructural performance as a function of both ground shaking intensity and structural response. Finally, the generalized methodology will be developed into a straightforward and practical series of implementation guidelines. The first guidelines to be developed will be those for which adequate research results are currently available. For the purposes of this Program Plan, four representative systems are planned to be used. Systems for which there would appear to be adequate research data available and which, in general, cover the range of structural systems and behaviors are:

- Steel moment frames
- Concrete moment frames
- Cantilever concrete wall systems
- Wood wall systems

Should adequate research data and funding be available, this effort could be extended to include other systems, including braced steel frames, coupled concrete walls, and various forms of masonry wall systems.

The Structural Performance Products Team consisting of a team leader, a researcher knowledgeable in the state of art and state of practice of structural analysis, and at least one engineer or researcher with extensive expertise and knowledge of the behavior and design requirements for each of the structural systems will perform these tasks. The team will include at least one expert practicing structural engineer routinely engaged in the design, evaluation, and upgrade of buildings. The Structural Performance Products Team will retain graduate student assistants and consultants to perform many of the development tasks.

Figure 4-1 presents the Structural Performance Products tasks that will be undertaken in Phase 1, along with a schedule for their completion (see also Table 3-1). These SPP tasks are detailed in the sections below.

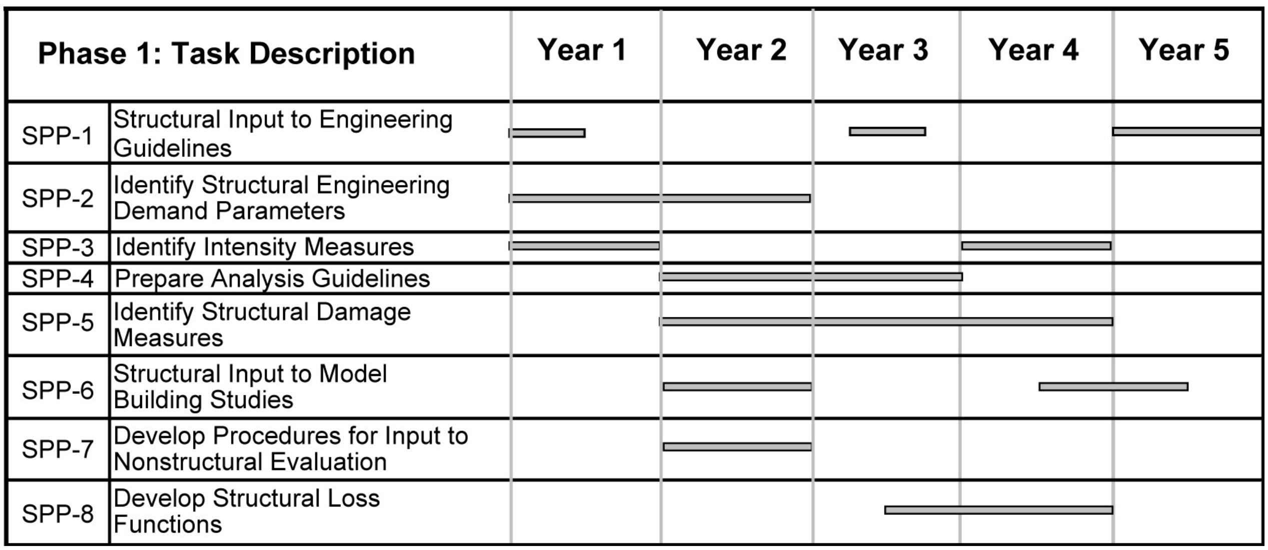


Figure 4-1 Phase 1: Schedule for structural performance products tasks.

4.1.1 Structural Input to Performance Assessment Guidelines (SPP-1)

The development of performance assessment guidelines will be jointly performed by the three Product Development Teams. The Structural Performance Products Team will be responsible for developing those portions of the guidelines relating to characterizing ground shaking hazards through intensity measures, modeling and analyzing structures to derive building-specific structural response functions and to develop input data for the evaluation of nonstructural components and systems, identification of structural damage measures, and development of structural fragilities.

The performance assessment guidelines will be developed incrementally over the five-year span of Phase 1. Preliminary draft guidelines will be developed in the first year of the program. This will enable the Structural Performance

Products Team to conceptualize the various design tasks that must be performed and understand how they fit into the overall process of performance-based seismic design. The draft guidelines developed in this initial effort will be updated, expanded, and added to throughout Phase 1 to incorporate the results of completed tasks in all three program areas. The final product of this task will be ready-for-publication sections of guidelines on structural performance assessment.

4.1.2 Identify Structural Engineering Demand Parameters (SPP-2)

Task SPP-2 will identify appropriate engineering demand parameters for use in assessing the performance of the four common structural systems (steel moment frame, concrete moment frame, wood wall, and concrete and masonry wall structures) and their components.

It is important that the recommended engineering demand parameters can be readily obtained from analysis, have relatively small variation at different levels of building response, and are meaningful for the purpose of predicting the various types of damage of significance to performance assessment for the particular structural systems. Engineering demand parameters may consist of peak quantities, such as peak interstory drift; cumulative quantities such as cumulative strain energy; or combinations of these such as are contained in the Park-Ang (1985) and related damage indices.

A list of the structural components and elements critical to performance for each framing system will be identified and engineering demand parameters developed. For each of these components and elements, information from existing research will be used to identify and characterize the engineering demand parameters. Pertinent existing research includes work done under the FEMA/SAC[1] Steel Project (for steel moment frames), the FEMA-funded CUREE Caltech[2] Wood-Frame Program (for wood walls), and relevant U.S.-Japan projects. Task SPP-2 will engage faculty and design professionals active in these projects in one or more workshops/meetings to assist in identifying the appropriate engineering demand parameters. This SPP-2 task will be coordinated with efforts undertaken in Task SPP-1 to incorporate findings into the performance assessment guidelines, with Task SPP-4 to develop analysis guidelines and with Task SPP-5 to develop guidelines for translating engineering demand parameters into component damage states.

[1] A joint venture partnership of the Structural Engineers Association of California, the Applied Technology Council, and California Universities for Research in Earthquake Engineering (CUREE), now known as Consortium of Universities for Research in Earthquake Engineering.

[2] California Institute of Technology

A summary report will be prepared describing the engineering demand parameters recommended for the performance assessment of components and elements of the selected framing systems, and detailed reasons for their selection. The report will also address considerations of reliability in predicting the engineering demand parameters using various methods of analyses (see Task SPP-4) and how well the values of the engineering demand parameters can be related to structural and nonstructural damage states (Tasks SPP-5 and NPP-7).

4.1.3 Identify Intensity Measures (SPP-3)

Task SPP-3 will identify earthquake hazard intensity measures, evaluate those that are efficient at predicting engineering demand parameter values, and develop recommendations for selection of appropriate ground motion representations for use in analysis. Task SPP-3 will document the appropriate statistical measures by which correlations between intensity measures and engineering demand parameters can be quantified. An internal report will be prepared and will recommend specific intensity measures to be used for assessing structural and nonstructural performance, characterization of ground motion for analysis, and methods of selecting and scaling ground motion records to conform to various values of the intensity measures.

Current practice is to use either peak ground acceleration or spectral acceleration at the fundamental period of building vibration as the primary intensity measure for performance assessment and design. One purpose of this task is to evaluate whether alternative intensity measure definitions are warranted and to recommend specific ways of characterizing ground motion, as a function of the intensity measures. The primary rational for using alternative intensity measures is to reduce the inherent variation in predicted values of engineering demand parameters for analyses performed using different ground motions scaled to the same intensity measure value. This task will provide and document the technical basis for the intensity measures recommended for use in building performance assessment.

Available information will be reviewed to develop a shortlist of alternatives that might yield less variation in engineering demand parameter predictions for the four structural systems identified above. One or more meetings to solicit input from researchers and design professionals knowledgeable on this subject will be held, with the ultimate goal of developing two or three alternative intensity measures to be considered for possible implementation. It is likely that the intensity measures may be distinguished on the basis of the performance level, that is, some intensity measures are known to have better efficiency in response prediction in either the elastic or inelastic range of behavior, but not both. An internal report will be prepared that documents the findings from this task.

Task SSP-3 will be performed by a project sub-team consisting of a geotechnical engineer or engineering seismologist, a structural analysis specialist, and a specialist in uncertainty evaluation. The project team will operate under the direction of the Structural Performance Products Team Leader. Efforts will be made to coordinate with and take advantage of work relevant work in this area concurrently being performed by the U. S. Geologic Survey and the three NSF earthquake engineering research centers.

4.1.4 Prepare Analysis Guidelines (SPP-4)

Task SPP-4 will develop and document one or more structural analysis methods for use in structural performance assessment and prediction of demands on nonstructural components and elements. This task will include consideration of soil-structure interaction and a statistical treatment of the uncertainties in earthquake hazards and structural response. These analysis methods will be used by design professionals to develop structural response functions that predict the values of engineering demand parameters for various levels of intensity measures and predict input demands for nonstructural components and systems suspended by or within the structure.

In Task SPP-4, one or more seismic analysis methodologies that will be included in the analysis guidelines will be identified. Emphasis will be placed on the use of inelastic response-history procedures with a rigorous treatment of uncertainties. Other analysis procedures will be examined, but will be included in the guidelines only if it is apparent that the procedures are sufficiently reliable to permit practical application. More traditional analysis procedures, for example nonlinear static analysis, may be found acceptable for application to structures within limited ranges of configuration and structural period. Linear procedures would be permitted only for: those few structures that would be expected to remain elastic, or nearly so, for all feasible levels of ground motion intensity; or for single degree-of-freedom structures where sufficient statistical data are available to characterize inelastic response based on elastic analysis and the uncertainty associated with elastic predictions of demands is well-defined.

Limitations of the selected analysis methods for representing extreme nonlinear behavior (e.g., near-collapse) will be documented. Analysis guidelines will consider how soil-foundation-structure-interaction (SFSI) effects should be considered, when significant, either by explicit modeling of soil-foundation elements or appropriate modification of the hazard and/or input ground motions, or a combination of these methods. Analysis guidelines will address appropriate statistical modeling of uncertainties in the earthquake hazard and structural response.

The analysis guidelines will be evaluated by application to the case study buildings developed under Task SPP-6. Both research-oriented (e.g., OpenSees, IDARC, ABAQUS) and commercial (e.g., SAP, ETABS, LARSA) software will be used for these studies. Both design professionals and researchers (faculty and graduate students) will contribute to the analysis/evaluation of the code-compliant buildings developed under Task SPP-6.

The analysis guidelines will address specific issues associated with calculating the engineering demand parameters identified in Tasks SPP-2 and SPP-7, and with appropriate representation of the earthquake hazard consistent with the intensity measures identified in Task SPP-3. Work on simpler analysis methods will require studies to calibrate bias and uncertainty parameters against inelastic response-history methods, but such work will only be undertaken if bias and uncertainty factors are available from other sources.

The results of Task SPP-4 will be incorporated into the analysis sections of the Performance Assessment Guidelines (SPP-1).

4.1.5 Identify Structural Damage Measures (SPP-5)

Task SPP-5 will develop definitions of appropriate damage measures for the four candidate framing systems. The damage measures will be used to form functions, relating levels of damage to response, as measured by the engineering demand parameters, and also to form loss functions, which relate the probable losses in casualties, repair/replacement costs and occupancy interruption to damage (see also Appendix A, Seismic Performance Assessment). Task SPP-5 will result in a series of chapters on the translation of engineering demand parameters into damage measures for the various structural systems and their components. Definition of the damage measures will be coordinated with the Risk Management Products Team, which will develop procedures and models to translate the damage measures into appropriate performance (loss) metrics.

As part of the task of identifying appropriate structural damage measures, it will be necessary to decide how performance is to be measured, for example, at the component, story, or system level, or a combination of these for differing levels of damage, ranging from modest to severe. How the damage measures will be integrated will depend to a large extent on how significant the damage is. For modest levels of damage, the main consequence of damage will likely be the need for repairs, which probably can be aggregated from a component level based on the repair costs and repair time. For more severe damage levels, which impair the safety of the occupants, more global descriptions of damage will probably be required.

Procedures for transformation of the quantitative engineering demand parameters into the selected damage measures will be developed. This work will be coordinated with the Nonstructural Performance Products Team and the Risk Management Products Team to include development of a generalized procedure to establish measures of building performance using values of structural and nonstructural component engineering demand parameters.

4.1.6 Structural Input to Model Building Studies (SPP-6)

Task SPP-6 will design structural systems for a series of case study buildings using current building code provisions. These models will then be subjected to the performance assessment procedure. One case study building will be developed for each of the four candidate structural systems. The goals of this task are threefold: (1) to test-drive the Performance Assessment Methodology and tools developed in Tasks SPP-1 through SPP-5 and SPP-7; (2) to serve as example applications in the eventual seismic Performance Assessment Guidelines, and (3) to provide information on the actual expected performance of representative buildings designed to the present building code. This task will be performed in coordination with the Nonstructural Performance Products Team, who will populate the model buildings with nonstructural systems and components, and the Risk Management Products Team, who will take the lead in assessing the performance of the case study buildings.

Case study building designs will be prepared for regions of high seismicity, such as are found in the western United States. Initial designs will follow the requirements of 2003 *NEHRP Recommended Provisions for Seismic Regulation of Buildings and other Structures* (BSSC, 2003). Foundation systems and site effects will be included in the designs to the extent that they will significantly impact the performance evaluation.

Once the designs are complete, the Risk Management Products Team will direct the use of the developing Performance Assessment Methodology to evaluate the performance capability of the designs. Graduate students will be involved with this activity. Each of the analysis methods presented in the Performance Assessment Guidelines will be used to evaluate the code-based designs. These evaluations will likely be repeated several times over the course of the project as the assessment methodology is developed and improved, to confirm the workability and completeness of the methodology, and to ensure that it can be implemented by design professionals.

4.1.7 Develop Procedures for Input to Nonstructural Evaluation (SPP-7)

Task SPP-7 will develop procedures for deriving the necessary data for evaluation of the performance of nonstructural components and systems from analysis of the structural system's response. These data are termed *nonstructural engineering demand parameters*. Nonstructural engineering demand parameters can generally be classified as those that are critical to the performance of deformation-sensitive and motion-sensitive components. Deformation-sensitive components include glazing, which under certain levels of lateral drift will break and fall out of its framing, and partitions, which will crack when laterally deformed. A typical engineering demand parameter for deformation-sensitive components is interstory drift. Nonstructural engineering demand parameters for motion-critical components can include floor acceleration, velocity, or displacement spectra (or alternative measures of floor motions that correlate with damage to nonstructural components).

Task SPP-7 will be undertaken in coordination with the Nonstructural Performance Products Team. The task is scheduled early in the Phase 1 5-year program, as it is critical to identify appropriate engineering demand parameters in order to coordinate activities between the Structural Performance Products and Nonstructural Performance Products Teams. Identifying nonstructural engineering demand parameters will help guide the development of analysis methods in Task SPP-4, the intensity measure selection in Task SPP-3, and the benchmark studies in Task SPP-6. Task SPP-7 will include one or more meetings to reach consensus between the Nonstructural Performance Products and Structural Performance Products Teams as to what engineering demand parameters are required from the structural analysis to evaluate nonstructural components and building contents. Discussions will also address the issue of what nonstructural components will influence the structural response, and therefore need to be modeled in the structural analysis.

During Task SPP-7, the analysis methods of Task SPP-4 will be developed so that demands (measured in terms of the selected nonstructural engineering demand parameters) on nonstructural components can be established as a function of intensity measure, as filtered through the structural system.

4.1.8 Develop Structural Loss Functions (SPP-8)

Under Task SPP-8, the Structural Performance Products Team will consult with and provide support to the Risk Management Products Team as it develops standardized procedures for deriving loss functions for structural components and systems as a function of the damage measures. Under Task SPP-8, the Structural Performance Products Team will also support the Risk Management Products Team in developing standard or default loss functions for typical structures comprising the four candidate structural systems.

4.2 Phase 1 Nonstructural Performance Products Tasks

The goal of the Nonstructural Performance Products tasks is to develop a practical and reliable generalized methodology for assessing the performance of nonstructural components and systems in buildings. This will include:

- Identifying appropriate intensity measures and nonstructural engineering demand parameters to characterize the response of these components and systems.
- Identifying preferred approaches to employing structural analysis to predict response as a function of intensity and nonstructural engineering demand parameters.
- Methods of predicting damage as a function of response or directly as a function of the input intensity measures.
- Development of procedures for assessing the probable consequences of damage to nonstructural components and systems in terms of probable casualties, repair/replacement costs, and downtime.

Work on the Nonstructural Performance Products tasks will be performed in parallel and in coordination with the Risk Management Products and Structural Performance Products tasks.

The Nonstructural Performance Products tasks will be conducted by a Nonstructural Performance Products Team. The team will be composed of a team leader, two researchers with experience in the investigation of the performance of nonstructural components, two structural design engineers, a practicing architect, a building mechanical engineer, and a building electrical engineer. At least one of the researchers will have familiarity with structural reliability methods and the development of damage functions. The Nonstructural Performance Products Team will also use a number of engineering consultants who will perform much of the literature search and data gathering efforts.

Figure 4-2 presents a schedule for the Nonstructural Performance Products tasks in Phase 1.

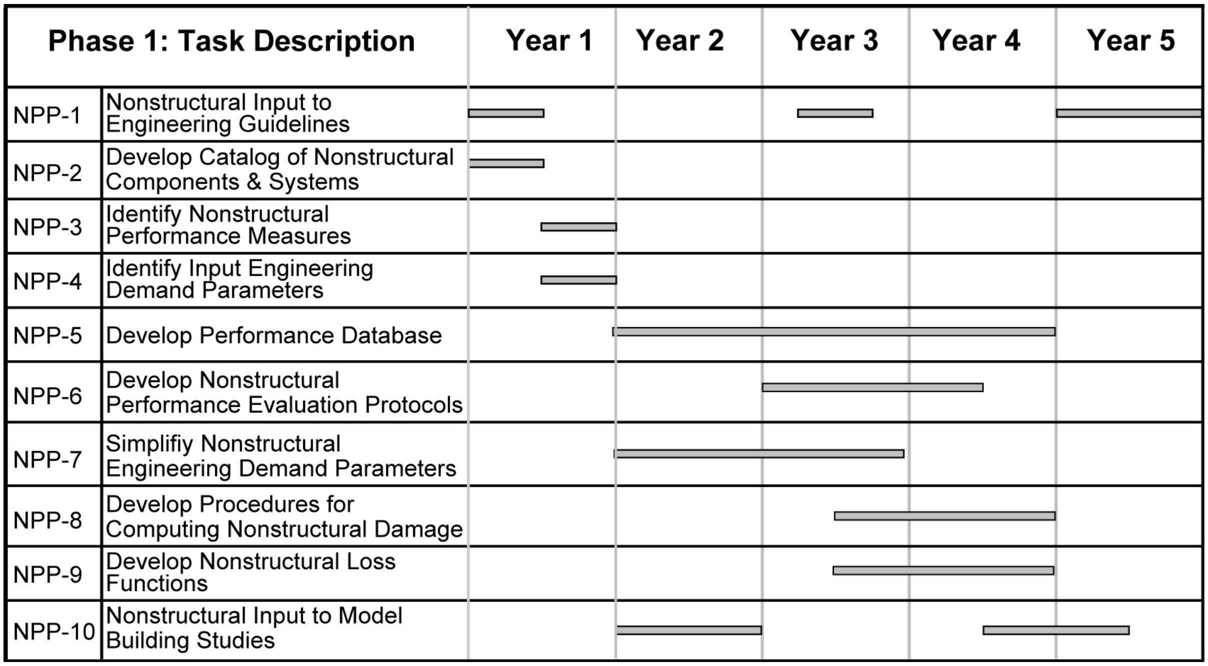


Figure 4-2 Phase 1: Schedule for nonstructural performance products tasks.

4.2.1 Nonstructural Input to Performance Assessment Guidelines (NPP-1)

The development of Performance Assessment Guidelines will be jointly performed by the three Product Development Teams. The Nonstructural Performance Products Team will be responsible for developing those portions of the guidelines that relate to identifying critical nonstructural components and systems in a building, determining their importance to the building's performance, characterizing the damagability of the nonstructural components and systems, and estimating the demands on these nonstructural components and systems as a function of the ground shaking hazard. The nonstructural sections of the guidelines will be developed in parallel with, and on the same schedule as, structural sections of the guidelines.

4.2.2 Develop Catalog of Nonstructural Components and Systems (NPP-2)

Task NPP-2 will identify, organize, and catalog the various types of nonstructural components, systems, and contents that are vulnerable to earthquake-induced loss and that are significant to the overall performance of the building. A literature search will be performed to identify past efforts to establish such an inventory and this inventory will be extended through the efforts of the Nonstructural Performance Products Team. In addition to looking at the importance of individual nonstructural components, Task NPP-2 will evaluate how components fit together to form systems (i.e. pumps, chillers, and fans are parts of an HVAC[3] system) and characterize the effects of damage to a single component on system functionality. The team will then identify the nonstructural systems that are typically present in various building occupancies, and if sufficient information is available, identify the weak links with regard to overall building performance. The team will take advantage of work published in *Installing Seismic Restraints for Mechanical Equipment* (VISCMA, 2002), *Installing Seismic Restraints for Electrical Equipment* (VISCMA, 2004a) and *Installing Seismic Restraints for Piping and Ducts* (VISCMA, 2004b). The NPP-2 Task will include interviewing owners of different types of facilities to determine the effects of potential damage on facility operation and may include walk-downs of selected buildings. The team will make judgments as to the significance of the various components and systems to overall building performance in order to trim the list of components to a manageable number.

This task will also support the eventual development of performance-based seismic design guidelines. As the inventory of nonstructural components and systems is developed, the team will identify the detail with which issues of design, installation, and maintenance of nonstructural components must be evaluated and for which detailed guidelines must be prepared.

Task NPP-2 will culminate with the development of an internal project report on identifying nonstructural components of significance and a scoping report on the issues to be evaluated in the overall project.

4.2.3 Identify Nonstructural Performance Measures (NPP-3)

Task NPP-3 will identify appropriate measures of nonstructural performance. The overall goal in this task is to identify the performance characterizations or damage measurements so that the evaluation and design methodologies developed in later tasks can be eventually targeted to definitive goals. Working with the performance definitions developed in the Structural Performance Products tasks, the team will quantify nonstructural performance and damage measures of significance (for example, loss of functionality, leakage rates, crack widths, tipping, breakage, etc.). This task will require a series of meetings with individuals with expertise regarding the seismic behavior of different component types. These experts will assist in cataloging different modes of behavior of the various component types. The deliverable for this task will be an internal project report on recommended nonstructural performance characterization and/or damage measures.

[3] Heating, ventilation, air-conditioning

4.2.4 Identify Input Engineering Demand Parameters (NPP-4)

Task NPP-4 will identify the input engineering demand parameters that are most appropriate for use in predicting the performance of various nonstructural components and systems. These input engineering demand parameters may include floor accelerations, interstory drifts, ductility demands, cumulative dissipated energy demands, floor response spectra, standardized floor response time histories, or other similar parameters. For nonstructural components mounted directly at grade, these input engineering demand parameters are actually ground motion intensity measures and may be the same intensity measures used for Structural Performance Assessment. For nonstructural components and systems mounted within or suspended on the structure, the input engineering demand parameters must be generated by structural analysis. Appropriate input engineering demand parameters may be different for the several types of nonstructural components.

A literature search will be performed to identify the input engineering demand parameters that have been suggested as appropriate for this purpose by various researchers and engineers. The Nonstructural Performance Products Team will compile these past recommendations into a comprehensive list, coordinate it with the inventory developed in Task NPP-1, review and evaluate these suggestions, and extend the assignment of engineering demand parameters to each of the components and systems present in the inventory using engineering judgment.

The product of Task NPP-4 will be an internal project report recommending the most appropriate input engineering demand parameters to be used for the performance assessment of various nonstructural components and systems.

4.2.5 Develop Performance Database (NPP-5)

Task NPP-5 will identify and obtain access to existing databases of seismic fragility data for nonstructural components. Such databases have been developed in the past by a number of groups including the Seismic Qualification Utilities Group, the Electric Power Research Institute, the Department of Energy, and others. Existing databases may be available from public agencies, proprietary sources, researchers, individual equipment and component vendors, and from test programs conducted in other countries (e.g., Canada). There might also be a substantial body of data available in the public domain in the form of reports on earthquake damage investigations. Much of this data has not yet been assembled into useful, searchable databases.

An important part of Task NPP-5 is developing of a comprehensive electronic database of building nonstructural components, including seismic fragility data. It will be organized using the inventory catalog developed in Task NPP-1 and will include component description, experience data, sanitized proprietary data, seismic qualification data, actual recorded motions, design capacities, and observed performance. The same data organization can be used as the basis for archiving data on the performance of nonstructural components collected following future earthquakes. Where possible, uncertainty statistics regarding component fragility will be included in the database.

4.2.6 Develop Nonstructural Performance Evaluation Protocols (NPP-6)

Given the many types of nonstructural components for which performance characteristics must be determined to permit practical implementation of performance-based design, it is imperative that suppliers of these components be encouraged to develop the necessary performance data. To ensure that the performance data developed by these individual manufacturers and suppliers are consistent and are useful in the performance assessment and design processes, standardized testing protocols and certification procedures will be developed for shake table testing, cyclic drift testing and component response testing.

The Nonstructural Performance Products Team will identify possible sources of funding for extensive testing. These sources will include equipment manufacturers, owners, insurers, and government agencies. Task NPP-6 might include developing collaborative efforts between equipment buyers and equipment manufacturers. The NPP Team will develop a consensus on the technical description of testing protocols and will develop a means of obtaining certification of tested equipment for various seismic regions, building types and usage, and locations within buildings.

Task NPP-6 will produce an internal project report that recommends standardized performance testing and certification procedures for nonstructural components. This data will be incorporated into the Performance Assessment Guidelines under Task NPP-1.

4.2.7 Simplify Nonstructural Engineering Demand Parameters (NPP-7)

Nonstructural components that are essentially rigid will experience the same motions as the ground or structure to which they are attached. For such components, the shaking at the attachment point can be used directly to estimate the level of damage sustained by the component. Flexible nonstructural components, however, will respond dynamically to the shaking at their point of attachments and may either amplify or attenuate the motions transmitted to them. To properly characterize the response and performance of such components, a dynamic analysis of the component or system of components is necessary to determine engineering demand parameters and levels of damage. However, given the large number of components present in a building of even moderate size, it is not practical to require such analyses except for a few, very important systems or components.

Under Task NPP-7, the Nonstructural Performance Products Team will develop approximate, simplified procedures to estimate the response parameters for flexible nonstructural components, given a set of input engineering demand parameters. This effort is primarily intended for distributed systems where it is difficult, without significant calculations, to determine the response engineering demand parameters. For example, for a piping system it may be necessary to know the stress or strain in individual piping connections, given input engineering demand parameters such as relative anchor displacements or floor spectra. The critical response engineering demand parameters will be identified for significant components. Procedures will be developed for each significant type of nonstructural component that is amenable to analysis.

Procedures will also be developed to determine generic response engineering demand parameters for a given set of input engineering demand parameters. For example, the procedures should permit estimates of the stresses or strains in a particular piping system given just the input engineering demand parameters, and without performing analysis of the system. Included in Task NPP-7 is development of estimates of uncertainty associated with determining the response engineering demand parameters for a given set of input without performing analysis.

4.2.8 Develop Procedures for Computing Nonstructural Damage (NPP-8)

Procedures will be developed in Task NPP-8 to convert the response engineering demand parameters for nonstructural components into damage measures. Damage measures could include loss of functionality, onset of leaking, failure of anchor bolts, and initial collapse of suspended ceilings, among others. This Task NPP-8 includes developing estimates of uncertainty associated with these damage measures.

Also as a part of this effort, the relationships of input engineering demand parameters to performance measures will be evaluated. It is likely that for many nonstructural components (for example, rigid components and those components that are purely drift-sensitive) there will be a direct relationship between the input engineering demand parameters and the damage measure.

For other nonstructural components, there may be only an indirect relationship (e.g., a piping system), requiring an intermediate step of analysis, per Task NPP-7.

The deliverable for Task NPP-8 will be an interim project report recommending procedures to establish damage as a function of either intensity measure or input engineering demand parameter. These procedures for completing nonstructural damage will also be incorporated into the Performance Assessment Guidelines.

4.2.9 Develop Nonstructural Loss Functions (NPP-9)

NPP-9, the Nonstructural Performance Products Team will provide consultation and support to the Risk Management Products Team in developing procedures for constructing loss functions for nonstructural components and systems in buildings. The Nonstructural Performance Products Team will also support the Risk Management Products Team in developing standard or default loss functions for buildings of typical occupancies.

4.2.10 Nonstructural Input to Model Building Studies (NPP-10)

Under Task NPP-10, the Nonstructural Performance Products Team will provide assistance to the Risk Management Products Team in their development of assessments of case study buildings. Under Task SPP-6, the Structural Performance Products Team will develop a series of case study building structures, each consisting of one of the four candidate structural systems, designed for a high seismicity site using the design criteria of FEMA 450. In Task NPP-10, the NPP Team will develop specifications of the nonstructural build-out of these structures to represent a series of different occupancies. The Risk Management Products Team will then assess the performance of these buildings, using the structural performance assessment procedures, as they are developed, as a means of evaluating the effectiveness and usefulness of the procedures.

4.3 Phase 1 Risk Management Products Tasks

The Risk Management Products (RMP) tasks are divided into two basic types. The first type will be a series of detailed technical tasks related to developing mathematical procedures for integrating and aggregating the hazard, response and damage information, developed by the SPP and NPP Teams, to develop projections of loss. The Structural Performance Products and Nonstructural Performance Products efforts will result in:

- Hazard curves that relate intensity of motion to probability of occurrence.
- Response curves that relate the response of the structure and nonstructural components mounted on the structure to the hazard.
- Damageability functions that relate the probable damage to the structure and nonstructural components and systems to the response.

The Risk Management Products Team will work with the Structural Performance Products and Nonstructural Performance Products teams to develop derivation procedures for loss curves that relate probable casualties, repair/replacement costs and occupancy interruption time to building damage. The Risk Management Products Team will then develop procedures to integrate the hazard with the building response, the response with the damage and the damage with the loss curves to project performance. These procedures will express loss estimates in various terms, including average annual loss, expected loss for a given probability of occurrence, and maximum bounded loss for a given probability of occurrence.

The second type of Risk Management Products tasks relates to communicating with stakeholders and decision-makers and ensuring that the means of expressing the performance outcomes of different design criteria decisions are useful to their decision-making processes.

The Risk Management Products tasks will be performed by a technical team that includes a team leader and associate team leader; a researcher, and an engineer, each of whom will have expertise in structural reliability methods and loss estimation, a professional cost estimator, to assist with the process of loss estimation; a structural engineer; an architect; and a building regulator to assist with tasks related to communication of performance issues. Figure 4-3 is a schedule for the various tasks, which are explained in more detail in the following sections.

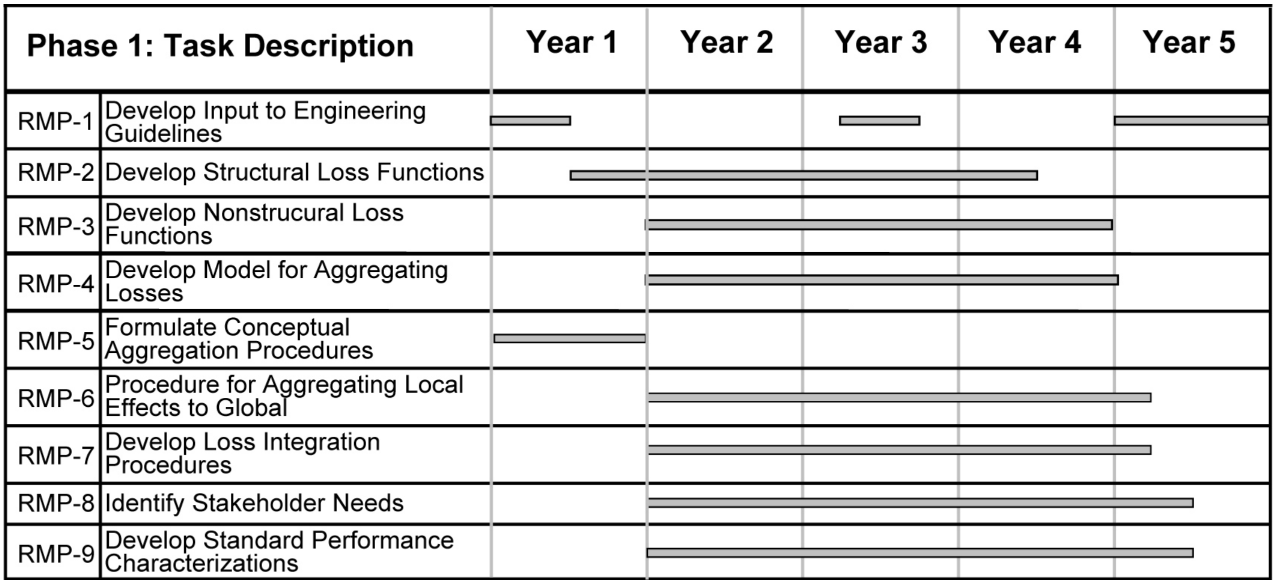


Figure 4-3 Phase 1: Schedule for risk management product tasks.

4.3.1 Develop Input to Performance Assessment Guidelines (RMP-1)

The development of the Performance Assessment Guidelines will be jointly performed by the three Product Development Teams. The Risk Management Products Team will be responsible for developing those portions of the guidelines that relate to methods of expressing performance and procedures for calculating performance, including development of loss functions and integration of the hazard, structural response, nonstructural response, and structural and nonstructural damage curves with the loss curves to derive performance assessments (see also Appendix A, Seismic Performance Assessment). The Risk Management sections of the Structural Performance Assessment Guidelines will be developed in parallel with, and under the same schedule as the Nonstructural Performance and Structural Performance sections.

4.3.2 Develop Structural Loss Functions (RMP-2)

In Task RMP-2 procedures will be developed for converting discrete descriptions of structural damage, as represented by the structural damage measures in Task SPP-5, into losses. Losses will be expressed as probable repair cost given damage, probable interruption of occupancy time given damage, and probable serious injury or loss of life given damage. In addition, standard loss functions will be developed for each of the four candidate structural systems.

The structural damage measures will consist of descriptions of structural damage. These may apply at the level of individual components (e.g., beam hinging, column spalling, brace buckling, wall cracking), at the element level (permanent interstory drift at a level), or other more global level (e.g., collapse). Structural damage measures will be expressed probabilistically in the form of damage functions that relate the probability of experiencing given damage as a function of the engineering demand parameters. Task RMP-2 will develop the procedures for converting the structural damage measures into meaningful loss terms for structural performance measurement. The procedures developed will then be implemented to develop standard structural loss functions for each of the four candidate systems.

Task RMP-2 will begin with discussions between the Risk Management Products Team and Structural Performance Products Team as to how structural damage measures might be best formulated to provide effective and efficient indicators for eventual compilation of losses and performance. For example, it may be that component spalling is a better measure of repair costs than residual drift. Task RMP-2 will involve meetings with experts in construction, and will explore alternative approaches using the case study buildings.

In the intermediate term, Task RMP-2 will focus on formulating the loss functions themselves. Appropriate indicators of loss will be developed for casualties (deaths and injuries), capital loss, and downtime.

4.3.3 Develop Nonstructural Loss Functions (RMP-3)

Task RMP-3 will develop standardized procedures to assess probable losses (casualties, capital loss, downtime) as a function of nonstructural damage. The nonstructural damage measures are descriptions of damage to nonstructural elements of buildings. These might apply to the individual component level (broken window), component assembly level (rate of leakage in a sprinkler riser or percent of windows in a wall likely to be broken), or system level (loss of function of an HVAC system). Nonstructural damage measures will be expressed probabilistically as damage functions that relate the probability of incurring various levels of damage either to levels of ground shaking, building or component response. Task RMP-3 will convert the nonstructural damage measures into meaningful terms for measuring performance. RMP-3 will also develop general procedures for determining nonstructural loss curves, as well as standardized default curves for common nonstructural components, assemblies and systems.

The Risk Management Products Team will work with the Nonstructural Performance Products Team to determine how nonstructural damage measures might best be formulated for effective and efficient indication of losses and performance. For example: pipe leaks should be characterized at appropriate vertical locations in a facility since the exposure of contents to damage will be greater for leaks that occur high in the building. The level of refinement of the nonstructural damage measures will vary depending on the function of the facility. The HVAC system for an entire office building, for example, might be represented by a single damage measure, while for a hospital, individual zones and equipment might be assigned independent damage measures.

Task RMP-3 will involve meetings with the Nonstructural Performance Products Team, consultation with experts in construction, and development of suggested strategies for the case study buildings. In the intermediate term, the effort will focus on the formulation of the loss curves themselves.

Appropriate indicators of loss will be developed for casualties, capital loss, and downtime. These will apply strictly at the component or component assembly level. For example, a loss curve for a pump might consist of an expected central value and distribution of the percentage of total loss for the pump itself. Thus, a damage measure such as fracture of a flange on input or output lines might convert to an expected loss of 40 percent of the cost to entirely replace the pump. Note that this cost (and loss) does not include the implications of the overall amount of repair involved for the system or the building, which must also be considered. System losses and building losses will be accounted for in the loss aggregation process. Casualty indicators for nonstructural components or component assemblies might include falling hazards (lights) and/or functional hazards (smoke evacuation). Downtime indicators are time-related (e.g., hours, days, months), at either the component or component assembly level.

4.3.4 Develop Model for Aggregating Losses (RMP-4)

Task RMP-4 will develop and maintain a procedure for aggregating losses from the various structural and nonstructural components and integrating them over the hazard curve to express losses in terms of the basic performance parameters useful to stakeholders and decision-makers. This may include development of an electronic spreadsheet tool or other software to serve as the framework for performance evaluation. Task RMP-4 will be completed in conjunction with the Structural Performance Products and Nonstructural Teams Products teams. The result will be a basic conceptual model for calculating expected losses in a building, as illustrated in Figure 4-4.

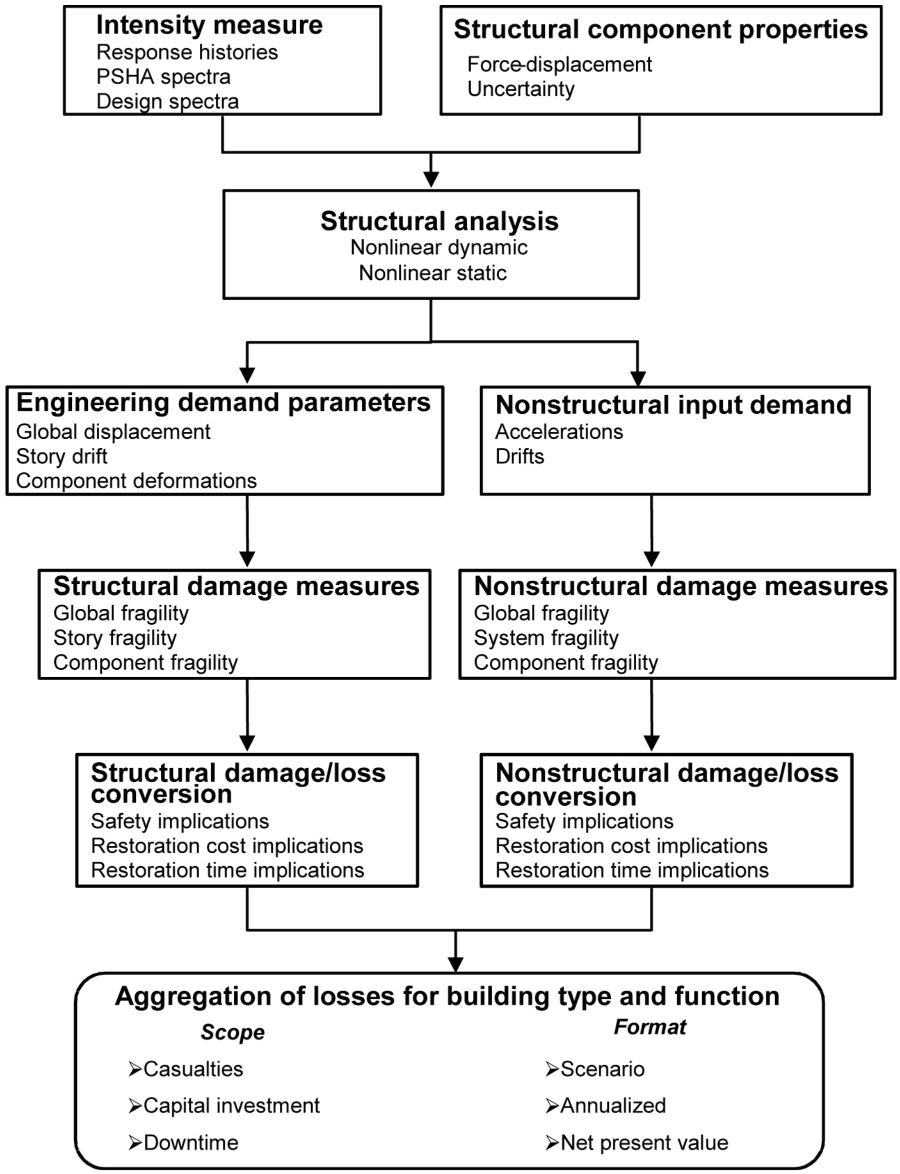


Figure 4-4 Loss aggregation process. Note: PSHA = probabilistic seismic hazard analysis

Specifically, this model for aggregating losses will:

1. Utilize response spectra, and ground motion records representative of these spectra, scaled to various intensity levels.
2. Incorporate nonlinear structural analysis to characterize the structural response to these ground motion representations and to develop functions that express the probable response of the structure as a function of intensity, in the form of various engineering demand parameters.
3. Convert the engineering demand parameters into structural and nonstructural damage measures at the entire building, story, component,

assembly, and system levels, expressed both deterministically and probabilistically.

4. Convert structural and nonstructural damage measures into deterministic or probabilistic losses using loss functions based on the type of building structure and occupancy.
5. Aggregate losses (casualties, capital loss, downtime) for the building using loss relationships that depend on the functional occupancy and use of the facility.

The basic model for aggregating losses will be developed and tested using the case study buildings.

Task RMP-4 is supported by a series of additional tasks, related to development of the basic methodology and procedures, and which are described further below.

4.3.5 Formulate Conceptual Aggregation Procedures (RMP-5)

Task RMP-5 will develop a preliminary performance assessment model that incorporates present methods of practice and will apply the model as a working platform by which to express performance in terms of probable losses. This is a critical short-term task involving:

- Documenting the current practices for loss estimation for individual buildings.
- Documenting the current research regarding loss estimation for individual buildings.
- Expanding the preliminary format to encompass the conceptual relationships among the critical parameters (intensity measures, engineering demand parameters, damage measures, etc.).
- Formulating a strategy for aggregating losses to determine building performance.
- Preparing an internal report for use by the project team to further expand the model.

Following completion of Task RMP-5, the preliminary aggregation procedures will be applied to the case study buildings developed under other tasks. This will enable improvements in the methodology to be developed on an incremental basis.

4.3.6 Procedure for Aggregating Local Effects to Global (RMP-6)

Task RMP-6 will develop a methodology to convert local measures of damage, for example buckled braces, cracked walls, or damaged sprinkler piping into a measure of total building loss. Interaction between individual local incidences of damage can significantly affect global loss, but the global loss is not simply the sum of losses that can be attributed to each individual element in the building, alone. As an example, the casualty rate in a building in which 10 percent of the columns have 10 percent or less of their original capacity might be relatively low if the damage is spread uniformly; or it may be relatively high if the damage is concentrated in a single floor. Also, capital losses are not simply the sum of the individual losses. Demolition and put-back costs, temporary relocation expenses, and soft costs can, in general, only be determined when the losses and performance implications are aggregated at the total building level. Consider, for example, that if a drywall partition is undamaged, it may have to be demolished and replaced, if structure behind this partition is damaged. Similarly, if both the structure and the partition are damaged, the partition need only be demolished and replaced one time. Task RMP-6 will explore these types of interdependencies and develop procedures for accounting for them in determining realistic estimates losses.

A particularly challenging part of Task RMP-6 relates to restoration of service in a damaged facility and calculation of downtime. This will be highly dependent on the occupancy of the individual building and its tolerance to functioning in less than ideal circumstances. Some building occupancies will be much more tolerant of operating in damaged buildings, or buildings under repair, than will other occupancies. An office building might be able to function, albeit at a somewhat impaired level, fairly soon after incurring damage, whereas surgical and other environmentally sensitive spaces in a hospital would take longer to resume function as they are less tolerant of dust, inadequate HVAC, and other effects of damage. Minor repair to a pharmaceutical manufacturing facility could result in many months of occupancy interruption, while the facility is recertified by federal licensing authorities. Task RMP-6 will attempt to develop occupancy-specific relationships to model these tolerances.

4.3.7 Develop Loss Integration Procedures (RMP-7)

Task RMP-7 will integrate conventional economic, probabilistic, and financial procedures into the performance model to provide procedures capable of expressing performance in various formats, including annualized loss, deterministic scenario loss, and time-based hazard-related losses. Results of this task will also include explicit consideration of uncertainty and reliability. Task RMP-7 will develop the procedures necessary to generate losses in these formats and transform them from one form to another.

In the short-term, Task RMP-7 will identify important procedures and the points at which they need to be incorporated into the overall model of Task RMP-4. The intermediate effort includes developing the basic procedures into modules within the model and testing the results. In the long-term, use of the basic procedures will be documented for implementation by practitioners. The loss integration procedures will have the capability to assess building performance in ways that are meaningful to the various stakeholders/decision-makers.

4.3.8 Identify Stakeholder Needs (RMP-8)

Task RMP-8 will continue the process of interfacing with stakeholder and decision-maker groups to understand their needs regarding consideration of building performance issues and the ways in which performance-based engineering products can be best related to their needs.

Initially, Task RMP-8 will focus on identifying and initiating contact with single representatives of important stakeholder groups and engaging these individuals in ongoing participation in the performance-based design development process. At this point, four principal stakeholder categories have been identified as important groups with which to develop such interface:

- Owners and managers
- Societal and governmental interests
- Financial managers
- Design professionals, consultants, and researchers

The first stakeholder category, owners and managers, are responsible for commissioning building design and construction, acquiring, maintaining and/or operating buildings and facilities. They make decisions about catastrophic risks that lead to action (or inaction) on a relatively narrow scale. Motivations generally spring from the best interests of the specific business or institution. Within the owner/manager category, three perspectives have been identified as important for interaction: investors, institutions and industry.

This distinction between these categories reflects the assumption that different stakeholder groups characteristically have different motivations and criteria for decisions relative to catastrophic hazard mitigation. It is important to capture these distinctions (e.g., investment risk, operational risks, and market risks).

The second stakeholder category includes those who represent broader societal and governmental interests. These individuals view catastrophic risk in a different context than do owners/managers. Their focus is on public safety and the impact of catastrophes on local/regional/national economies. Their decisions relate primarily to public policy, legislation and administration. The societal/governmental category is separated into three perspectives for focus groups: policy-makers, regulators, and special interest and advocacy groups. This reflects the different levels of sophistication, scope of decision-making and problem-solving ability, and types of criteria used by the three groups (e.g., policy-makers are making broadly applicable decisions for the community; regulators are considered more as "enforcers," focused on the problem one building at a time; and special interest and advocacy groups "speak" for the interested and affected public).

The third stakeholder category is primarily financial in nature. The owner/manager and the societal/governmental stakeholder categories have a direct stake in decisions about risks associated with buildings (e.g., protect the assets and protect the community interest). Financial stakeholders, however, have an indirect interest in building performance decisions made by others. Their decisions relate primarily to whether or not to assume risk associated with buildings and at what compensation level. The financial category might be represented by three focus groups: lenders, insurers, and securities packagers.

Financial stakeholders differ from the previous two categories in that the stake is indirect: the concern is the financial risk associated with the decision to finance or assume risk, rather than in protection of people or owned assets. The three groups (lenders, insurers, and securities packagers) represent different views with respect to when and how the financial decisions are made, which in turn may impact how they characterize the risk and performance issues. Financial stakeholders tend to use very complex statistical and mathematical tools for decision-making.

The fourth category of stakeholders includes design professionals, consultants, and researchers. The development of performance-based design capability has advanced primarily within this group, yet many are not familiar or conversant in this field. The design and consulting communities are the conduits through which performance-based design will be implemented. Awareness of performance-based design must be expanded to include input from both technical development personnel and those who implement performance-based design.

In the intermediate and longer terms, stakeholder categories will be expanded in order that Task RMP-8 activities may encounter broader perspectives. For each of the four stakeholder groups, Task RMP-8 will identify and recruit two to three additional representatives from the stakeholder groups. These groups will meet periodically with the Risk Management Products Team and others to monitor task progress and advise on the development of the Risk Management Products, particularly as it relates to Risk Management Products Task 8. Members of the Risk Management Products Team will serve as liaisons with the group representatives. Group members will be selected as much as possible from relatively high level and influential candidates. This will result in the development of longer term relations that will facilitate the transfer of performance-based design technology to the service and research stakeholders over time.

4.3.9 Develop Standard Performance Level Characterizations (RMP-9)

Task RMP-9 will develop procedures to express the risks that are the consequence of structural and nonstructural design decisions into formats that are as directly useful as possible to the various stakeholder and decision-maker groups. In the short term, Task RMP-9 entails the assembly of basic information on the decision-making processes commonly used by various stakeholder groups. This information will be gathered in meetings with the initial stakeholder representatives and summarized in internal written summaries. In the intermediate term, the Risk Management Products Team will develop written pieces to illustrate basic options (e.g., annualized loss, scenario loss, time-based objectives) for discussion of them with the various groups. Based on feedback, preferred methods of expressing loss and performance will be determined. In the long term, the RPM Team will refine the basic options into standardized recommendations based on individual stakeholder perspectives.

Chapter 5

Phase 2: Developing Performance-Based Seismic Design Procedures and Guidelines

5.1 Phase 2 Objectives

Chapters 3 and 4 of this report present the detailed work plan for Phase 1 of this Program Plan to develop a next-generation seismic performance assessment methodology and accompanying engineering guidelines. Engineers will be able to use those guidelines immediately in implementing performance-based design of new buildings and performance-based upgrade of existing buildings. To do this, however, they will first need to develop preliminary designs on which to conduct a performance assessment. Some engineers, particularly those with extensive experience in earthquake-resistant design, will be able to develop preliminary designs that are able to satisfy the desired performance objectives without extensive modification. Other engineers, however, will have difficulty developing preliminary designs that will be capable or nearly capable of meeting the desired performance objectives. Unless further guidance is provided, some engineers may find implementation of performance-based design to be time consuming and costly in many cases.

Phase 2 this Program Plan, *Developing Performance-Based Seismic Design Procedures and Guidelines*, responds to this need, by developing additional tools needed to allow wider application of the next-generation performance-based design approach. Phase 2 will use and refine the Seismic Performance Assessment methodology developed in Phase 1, and enable next-generation performance-based design practice to become efficient and economical and thereby, acceptable and implementable. Specifically, Phase 2 will address additional issues and develop guidelines necessary to:

- Assist decision-makers in selecting appropriate performance objectives for buildings of different occupancies.
- Assist design professionals in identifying appropriate strategies for structural design of buildings to achieve specific performance objectives.

- Assist design professionals in developing efficient preliminary designs that will require relatively little iteration during the design process,
- Quantify the performance capability of typical buildings designed to current prescriptive building codes, so that the lack of consistency in current performance and the advantages of performance-based design approaches is evident.
- Provide for direct prescriptive performance-based design of simple buildings to achieve different performance objectives.

5.2 Phase 2 Description of Work

Phase 2 of this Program Plan will develop these additional tools and capabilities. Work to be performed under Phase 2 can be broadly classified into the following categories:

- Identify the key decision-making parameters and processes used by different stakeholder groups.
- Identify appropriate performance objectives for buildings of different occupancies.
- Develop simple tools to assist decision-makers in selecting appropriate performance objectives.
- Identify the performance consequences of various strategies for design, procurement, and construction.
- Identify the performance consequences of various quality assurance strategies.
- Develop simple tools for selecting appropriate design strategies to achieve different performance objectives.
- Develop guidelines to assist stakeholders in taking advantage of the benefits of performance-based design, including considerations of maintenance.
- Develop guidelines for design professionals to assist them in implementing performance-based design.

5.3 Summary of Phase 2 Product Tasks

Work in each technical area will be performed by one of the three Product Development Teams organized in Phase 1: the Structural Performance Products Team, the Nonstructural Performance Products Team, and the Risk Management Products Team. Though some changes in personnel might be appropriate, the members of the Product Development Teams will generally be the same as those empanelled in Phase 1. A summary of Phase 2 tasks to be performed by each of these teams is provided in the subsections that follow. Detail descriptions of Phase 2 tasks are provided in Chapter 6.

5.3.1 Structural Performance Products Tasks

Principal Phase 2 tasks to be performed by the Structural Performance Products (SPP) Team will include:

- SPP-9: Identify the contributions to performance, as measured in life loss and injuries, direct repair and replacement cost and downtime, of various types of structural damage for buildings of different structural systems, occupancies, and eras and styles of construction.
- SPP-10: Identify the effects of various structural parameters, including stiffness, strength, ductility, and damping, on life loss and injuries, direct repair and replacement costs and downtime in buildings of various occupancy, structural systems and eras and styles of construction.
- SPP-11: Identify preferred structural strategies for achieving various performance objectives in new buildings of different occupancy and structural systems.
- SPP-12: Identify preferred structural strategies for upgrade of existing buildings of different eras and construction types to achieve various performance objectives in buildings of different structural systems.
- SPP-13: Prepare structural input to performance-based design guidelines for performance-based design.

5.3.2 Nonstructural Performance Products Tasks

Principal Phase 2 tasks to be performed by the Nonstructural Performance Products team will include:

- NPP-11: Identify the contribution to performance, as measured in life loss and injuries, direct repair/replacement cost, and downtime of various nonstructural components and systems in buildings. Different eras of construction and different design and installation criteria will be considered, as well as the effects of different occupancies and structural characteristics.
- NPP-12: Identify the effectiveness of current code procedures in reducing the consequences of nonstructural performance in terms of life loss and injuries, direct repair/replacement costs, and downtime in buildings of different occupancies, and structural system types.
- NPP-13: Identify the effectiveness of various alternative design strategies for reducing life loss and injuries, direct repair and

replacements costs, and downtime consequences of nonstructural component and system performance in buildings of different occupancies, structural systems, and eras of construction.

- NPP-14: Develop preferred nonstructural design strategies for achieving various performance objectives in buildings of different occupancy types, structural systems, and eras of construction.
- NPP-15: Prepare input to performance-based design guidelines.

5.3.3 Risk Management Products Tasks

Principal Phase 2 tasks to be performed by the Risk Management Products (RMP) Team will include:

- RMP-10: Identify the key performance concerns of different stakeholder communities and types of decision-makers.
- RMP-11: Identify the key performance parameters for buildings of different occupancies.
- RMP-12: Identify the preferred decision-making models of different types of decision-makers.
- RMP-13: Develop simplified decision-making aids that will assist decision-makers to select appropriate building performance objectives.
- RMP-14: Explore the performance capability of typical buildings designed in accordance with current building code procedures using typical contemporary procurement, construction and quality assurance practices and comparing these against the needs of various stakeholders.
- RMP-15: Explore the performance capability of typical existing buildings designed in accordance with the standards prevalent during different eras and in different regions of the nation, for buildings of various occupancies and structural system types.
- RMP-16: Develop guideline documents to assist various decision-maker and stakeholder groups to achieve the maximum possible benefit from performance-based design.
- RMP-17: Provide input to performance-based engineering guidelines for seismic design.

The Risk Management Products Team will play a significant role in support of the work performed by the Nonstructural Performance Products and Structural Performance Products Teams. Much of the work performed by these two teams will consist of exploring the effects of various design strategies on building performance capability. This will require that a series of model building designs be developed and their performance capability assessed with respect to the performance of both structural and nonstructural components and systems. It is anticipated that the Risk Management Products Team will implement these performance assessments using the seismic performance assessment methodology developed in Phase 1.

5.4 Phase 2 Project Management

Project management will be performed under the same management structure described for Phase 1, and illustrated in Figure 3-1. Project management and oversight will be conducted using the same procedures and the same committees, including a Project Management Committee, Project Technical Committee, and Project Steering Committee.

5.5 Phase 2 Projected Program Costs and Schedule

Phase 2 of this Program Plan is intended to be accomplished in five years, contingent on the availability of sufficient levels of funding to enable the necessary work to be performed in the planned sequence. Figure 5-1 presents an overall summary of tasks and schedule for the originally planned Phase 2 work. Detailed descriptions of Phase 2 tasks are provided in Chapter 6.

The original Phase 2 total projected project costs were estimated at approximately $10 million in 2004 dollars. Estimates of personnel and other costs associated with the Phase 2 tasks of this Program Plan have been developed using prevailing labor costs common to projects of this type at the time this plan was prepared, and do not include escalation due to changes in the value of money, labor rates, internal government costs, or inflation. Table 5-1 presents an overall estimate for Phase 2 broken down by Product Development Area. Table 5-2 presents a detailed breakdown of these costs by specific task and shows how these costs were intended to be distributed throughout the program.

Table 5-3 and Table 5-4 present an overall picture of the Phase 2 reduced-scope program prepared at the request of FEMA. The budget for the reduced-scope program is approximately 50% of that for the original program. Table 5-3 presents an estimate for the reduced scope costs for Phase 2 broken down by Product Development Area, and Table 5-4 presents a detailed breakdown of reduced-scope costs by specific tasks.

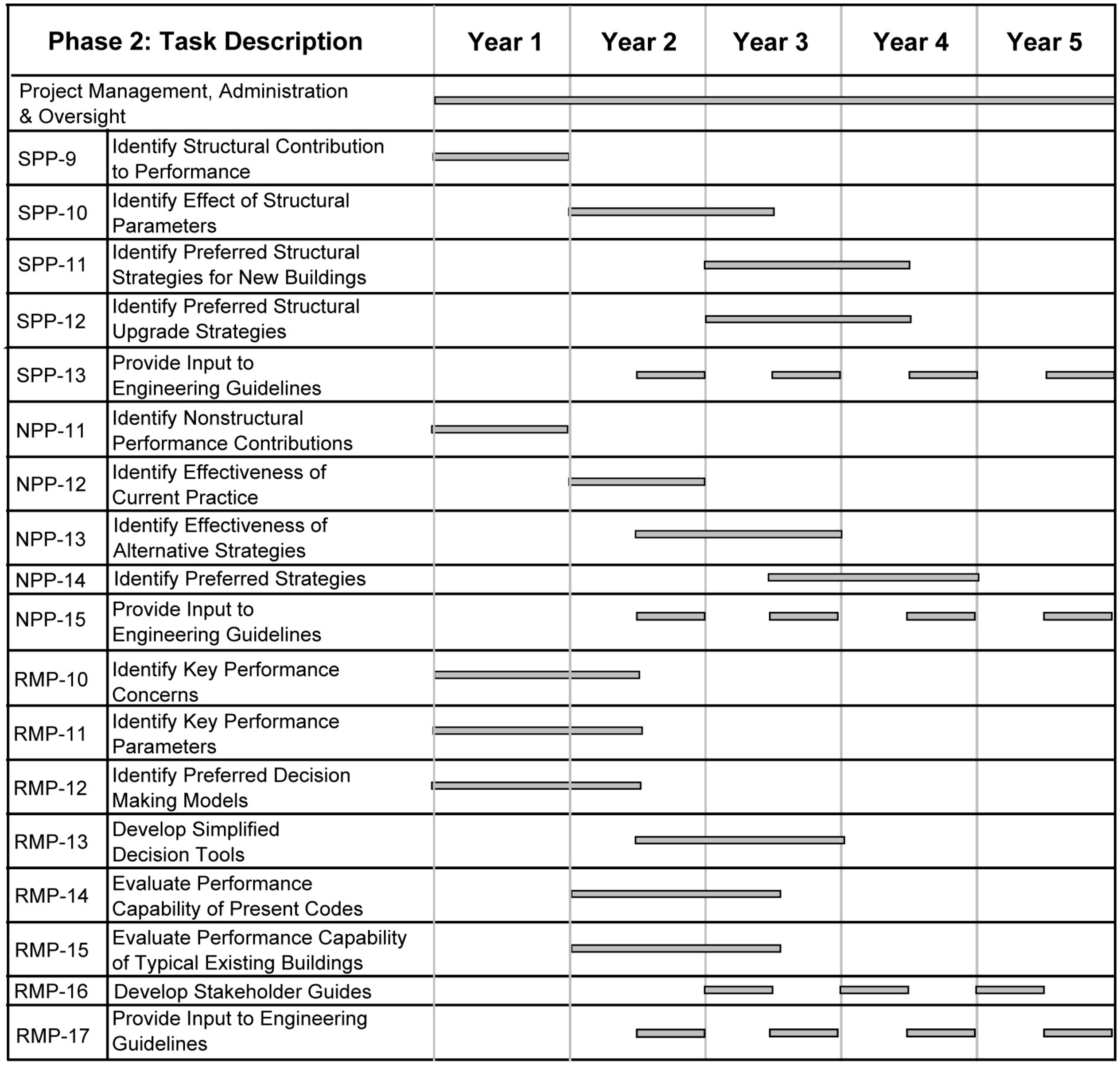


Figure 5-1 Summary of tasks and schedule for Phase 2: *Developing Performance-Based Seismic Design Procedures and Guidelines*. Phase 2 begins upon completion of Phase 1.

Table 5-1 Original Projected Program Costs by Product Development Area, Phase 2: Development of Performance-Based Seismic Design Guidelines

Product Development Area/Cost Element	Cost ($1,000)
Structural Performance Products	$2,635
Nonstructural Performance Products	1,440
Risk Management Products	2,200
Project Management, Administration, Oversight (Review), and Other Costs (Travel, Communications, Supplies and Equipment)	3,375
Total	$9,650

Table 5-2 Original Phase 2 Projected Program Costs by Task and Year ($1,000)

Task	Year 1	Year 2	Year 3	Year 4	Year 5	Total
SPP-9 Identify Structural Contribution to Performance	$560	-	-	-	-	*560*
SPP-10 Identify Effect of Structural Parameters	-	520	255	-	-	*775*
SPP-11 Identify Preferred Structural Strategies for New Buildings	-	-	330	220	-	*550*
SPP-12 Identify Preferred Structural Upgrade Strategies	-	-	220	220	110	*550*
SPP-13 Provide Input to Design Guidelines	-	50	50	50	50	*200*
SPP Total	**560**	**570**	**855**	**490**	**160**	***2,635***
NPP-11 Identify Nonstructural Performance Contributions	560	-	-	-	-	*560*
NPP-12 Identify Effectiveness of Current Practice	-	100	-	-	-	*100*
NPP-13 Identify Effectiveness of Alternative Strategies	-	110	220	-	-	*330*
NPP-14 Identify Preferred Strategies	-	-	80	170	-	*250*
NPP-15 Provide Input to Design Guidelines	-	50	50	50	50	*200*
NPP Total	**560**	**260**	**350**	**220**	**50**	***1,440***
RMP-10 Identify Key Performance Concerns	170	80	-	-	-	*250*
RMP-11 Identify Key Performance Parameters	170	80	-	-	-	*250*
RMP-12 Identify Preferred Decision-Making Models	170	80	-	-	-	*250*
RMP-13 Develop Simplified Decision Tools	200	-	-	-	-	*200*
RMP-14 Evaluate Performance Capability of Present Codes	100	-	-	-	-	*100*
RMP-15 Evaluate Performance Capability of Typical Existing Buildings		225	225	-	-	*450*
RMP-16 Develop Stakeholder Guides		0	200	200	100	*500*
RMP-17 Provide Input to Design Guidelines		50	50	50	50	*200*
RMP Total	**810**	**515**	**475**	**250**	**150**	***2,200***
Project Management, Oversight & Administration	475	475	475	475	475	*2,375*
Other Direct Costs	200	200	200	200	200	*1,000*
Total	**$2,605**	**$2,020**	**$2,355**	**$1,635**	**$1,035**	***$9,650***

Table 5-3 Reduced-Scope Projected Program Costs by Product Development Area, Phase 2: Development of Performance-Based Seismic Design Guidelines

Product Development Area/Cost Element	Cost ($1,000)
Structural Performance Products	$1,140
Nonstructural Performance Products	650
Risk Management Products	1,070
Project Management, Administration, Oversight (Review), and Other Costs (Travel, Communications, Supplies and Equipment)	2,140
Total	$5,000

Table 5-4 Reduced-Scope Phase 2 Projected Program Costs by Task and Year ($1,000)

Task	Year 1	Year 2	Year 3	Year 4	Year 5	Total
SPP-9 Identify Structural Contribution to Performance	$250	-	-	-	-	*250*
SPP-10 Identify Effect of Structural Parameters	-	260	50	-	-	*310*
SPP-11 Identify Preferred Structural Strategies for New Buildings	-	-	130	100	-	*230*
SPP-12 Identify Preferred Structural Upgrade Strategies	-	-	100	100	50	*250*
SPP-13 Provide Input to Design Guidelines	-	25	25	25	25	*100*
SPP Total	**250**	**285**	**305**	**225**	**75**	***1140***
NPP-11 Identify Nonstructural Performance Contributions	250	-	-	-	-	*250*
NPP-12 Identify Effectiveness of Current Practice	-	50	-	-	-	*50*
NPP-13 Identify Effectiveness of Alternative Strategies	-	50	100	-	-	*150*
NPP-14 Identify Preferred Strategies	-	-	40	60	-	*100*
NPP-15 Provide Input to Design Guidelines	-	25	25	25	25	*100*
NPP Total	**250**	**125**	**165**	**85**	**25**	***650***
RMP-10 Identify Key Performance Concerns	80	40	-	-	-	*120*
RMP-11 Identify Key Performance Parameters	80	40	-	-	-	*120*
RMP-12 Identify Preferred Decision-Making Models	80	40	-	-	-	*120*
RMP-13 Develop Simplified Decision Tools	80	-	-	-	-	*80*
RMP-14 Evaluate Performance Capability of Present Codes	80	-	-	-	-	*80*
RMP-15 Evaluate Performance Capability of Typical Existing Buildings	-	100	100	-	-	*200*
RMP-16 Develop Stakeholder Guides	-	0	100	100	50	*250*
RMP-17 Provide Input to Design Guidelines	-	25	25	25	25	*100*
RMP Total	**400**	**245**	**225**	**125**	**75**	***1070***
Project Management, Oversight & Administration	250	250	250	250	240	*1240*
Other Direct Costs	100	200	200	200	200	*900*
Total	**$1,250**	**$1,105**	**$1,145**	**$885**	**$615**	***$5,000***

Chapter 6

Phase 2: Developing Performance-Based Seismic Design Procedures and Guidelines— Product Tasks

6.1 Phase 2 Structural Performance Products Tasks

The purpose of the Phase 2 Structural Performance Products tasks is to develop recommendations for selection and design of structural systems that can be effectively used to achieve a range of performance goals in new building design and existing building upgrade projects. Structural systems affect the performance of buildings—as measured in casualties, economic loss related to repair and replacement and occupancy interruption—through two primary behaviors. First, structural systems themselves are vulnerable to damage, and therefore can directly cause casualties, require repair, and result in unsafe conditions that prevent building occupancy and use. Second, structural systems transmit demands to nonstructural components and systems, in the form of accelerations and interstory drifts, in turn damaging these nonstructural building components. Design of structural systems to achieve desired performance, whether in new buildings or upgrade of existing buildings must consider both of these effects. Therefore, the Structural Performance Products Team will work closely with the Nonstructural Performance Products Team in developing appropriate strategies.

Structural performance products tasks include identifying the importance of structural damage as a contributor to the basic performance metrics, and evaluating the effectiveness of various structural design strategies such as stiffening, strengthening, improving ductility, etc., to reducing building losses. Task SPP-8 will identify preferred combinations of these structural parameters to achieve desired performance goals. Tasks will culminate with development of procedures for selection of appropriate structural design strategies to achieve desired performance goals, development of preliminary design criteria that will enable designers to efficiently implement performance-based design methods, and presentation of the results of these tasks in Performance-based Design Guidelines.

Figure 6-1 presents a proposed schedule for the Phase 2 Structural Performance Product tasks, which are described in more detail in the following sections.

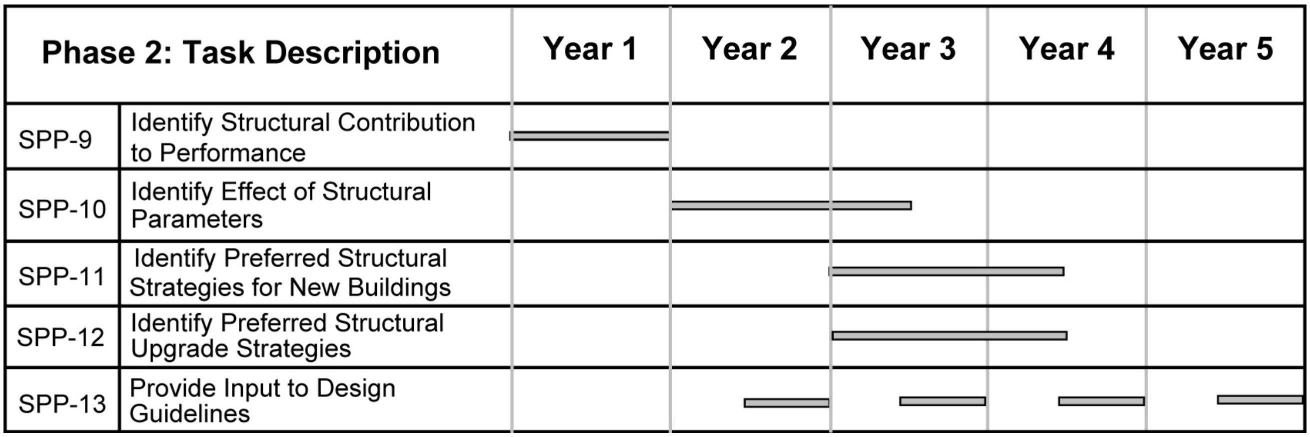


Figure 6-1 Phase 2: Schedule for structural performance products tasks

6.1.1 Identify Structural Contribution to Performance (SPP-9)

Task SPP-9 will investigate the relationship between structural performance and overall building performance. Since it is already clear that the performance of buildings with fragile structural systems, such as unreinforced masonry buildings and nonductile concrete frame buildings, will be dominated by the high potential for structural collapse and total building loss, Task SPP-9 will focus on buildings designed to modern code requirements and which have low risk of collapse. Task SPP-9 will be run in parallel with Task NPP-10, and will extract data from the evaluations performed under that task to identify the extent that structural damage in modern well-designed structures affects overall building performance. This information will be used to guide later tasks that are focused on developing design strategies intended to improve the seismic performance characteristics of buildings.

6.1.2 Identify Effect of Structural Parameters (SPP-10)

Task SPP-10 will identify the effect that basic structural design parameters—that is stiffness, strength, period, damping and ductility—have on overall building performance. Increases in structural stiffness, for example, reduce interstory drift, but can result in higher floor response accelerations and higher structural forces at low levels of structural response. This might reduce damage to drift-sensitive nonstructural components, but increase damage to acceleration-sensitive components as well as to structural components. Increased strength may reduce damage to structural components, but transmit higher floor accelerations to nonstructural components.

In this task, a series of case-study buildings will be developed, and then subjected to a series of parametric performance evaluations in which structural design parameters (e.g., stiffness, strength, and damping) are varied. The effect on overall building performance, as well as the individual performance of structural and nonstructural elements, will be evaluated. Relationships between these various parameters and building performance will be developed for use in preliminary design to determine appropriate target values for these parameters.

6.1.3 Identify Preferred Structural Strategies for New Buildings (SPP-11)

Task SPP-11, along with the results of Tasks SPP-9 and SPP-10, will be evaluated to develop procedures for identifying appropriate design strategies and preliminary design procedures for new building construction. Strategies will address selection of appropriate systems, and the preliminary design procedures will address configuration and proportioning of the system in a manner that is consistent with the selected performance objectives.

6.1.4 Identify Preferred Structural Upgrade Strategies (SPP-12)

Task SPP-12 is parallel to Task SPP-11 and will develop procedures for identifying appropriate design strategies and preliminary designs for the seismic upgrade of existing buildings. The principal difference between Task SPP-12 and Task SPP-11 is that, in addition to providing protection for the new structure and the nonstructural components and systems, the upgrade systems must be sufficient to protect the existing structural systems, which are often fragile. Task SPP-12 will entail performance evaluations of a series of case-study existing buildings with a number of different upgrade strategies, so that the effectiveness of these strategies on the performance of the building as a whole can be determined.

6.1.5 Provide Input to Design Guidelines (SPP-13)

Task SPP-13 will develop structural sections of Performance-based Design Guidelines focused on developing preliminary designs of structural systems in new building construction and for existing building upgrades, to satisfy various performance objectives. The Performance-based Design Guidelines will include information on characterizing earthquake hazards, selecting an appropriate structural upgrade or design strategy and developing a preliminary structural design. The Seismic Performance Assessment guidelines developed under Phase 1 will be used to confirm that the preliminary design is actually capable of providing the desired performance and as a tool to adjust preliminary designs, as necessary to achieve desired performance.

6.2 Phase 2 Nonstructural Products Tasks

The purpose of the Phase 2 Nonstructural Performance Products tasks is to develop recommendations for design and installation practices that can be effectively used to achieve a range of performance goals in new building design and existing building upgrade projects. One of the significant problems associated with doing this is that there is no clear understanding as to how significantly nonstructural damage contributes to casualties, economic loss, and occupancy/use loss. There is a general, but unverified, belief that structural damage (as opposed to nonstructural damage) is the primary contributor to casualties. Similarly, there is a belief that nonstructural losses tend to dominate repair costs, particularly for moderate levels of shaking intensity. It is not clear whether structural or nonstructural damage is most significant to occupancy interruption losses. Before an effective strategy for mitigating potential losses due to nonstructural damage can be developed, it is important to quantify the contribution of nonstructural damage to these various types of building losses.

Presuming that the contribution of nonstructural damage to potential losses is significant, it next becomes important to develop effective strategies to improve building performance through mitigation of these losses. Several basic approaches are hypothetically possible, including altering the structural system to moderate the demands on the nonstructural components and systems, reducing the damageability of these components and systems through improved design practices, as well as the basic procedures for procuring these building components, which presently relies heavily on field design by the installation contractor. The effectiveness of each of these approaches needs to be evaluated to recommend appropriate strategies as part of the Performance-based Design Guidelines. Further, since these nonstructural effects are likely to be dependent on the seismicity at the building site and the type and age of building construction, Phase 2 will undertake an extensive parametric study, as described in the individual NPP Tasks outlined below. Figure 6-2 provides a projected summary schedule for these tasks.

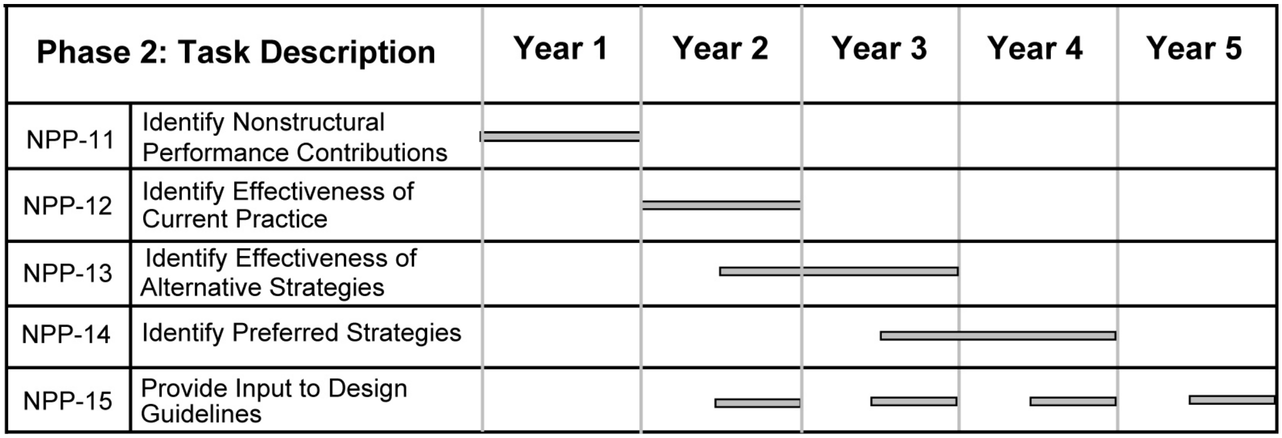


Figure 6-2 Phase 2: Nonstructural Performance Products task schedule.

6.2.1 Identify Nonstructural Performance Contributions (NPP-11)

Task NPP-11 will identify the contribution of nonstructural damage to casualties, repair costs, and occupancy/use interruption times in buildings of various types and eras of construction, and in several seismic zones. Performance, measured by estimated losses will be evaluated for a series of case study buildings considering two basic conditions for each building. The first condition consists of the building with nonstructural components and finishes present, but with these components being seismically rugged, (i.e., not prone to damage). The second case consists of the same buildings, but with nonstructural components and systems that have damage potential that is more typical of those found in real buildings. The projected difference in losses between the buildings with rugged nonstructural components and those with fragile nonstructural components will indicate the extent that the nonstructural components contribute to these various performance measures.

It is important to note that this same data cannot be attained by evaluating the performance of bare shell buildings and comparing it against performance of buildings that have been built out with nonstructural components. This is because there may be significant costs associated with the demolition and repair of nonstructural components that were not damaged, but which must be removed and then replaced in order to allow structural repairs to occur.

For the purposes of Task NPP-11, it will probably not be necessary to evaluate the performance of a large number of buildings. Rather, the performance of a range of structural types will be evaluated, including structurally fragile and structurally rugged building types, structurally stiff and structurally flexible building types, and nonstructural systems that are relatively rugged, as represented by current practice in regions of high seismicity, and those that are relatively fragile, as represented by other types of practice.

A range of performance assessments will be performed. It will be important to understand the relationship of nonstructural performance relative to structural performance at different ground motion intensity levels. Thus, in addition to performing probabilistic evaluations that consider the entire range of hazards, it will be important to conduct scenario evaluations that permit examination of the relative contributions of structural and nonstructural damage at different intensity levels.

The Structural Performance Products Team will assist in Task NPP-11 by developing structural designs for evaluations. The Risk Management Products Team will assist by performing the evaluations. The Nonstructural Performance Products Team will take the lead in developing the nonstructural components and systems inventories for these structures and will interpret the results of the studies to obtain data that are useful for formulation of design recommendations.

6.2.2 Identify Effectiveness of Current Practice (NPP-12)

Task NPP-12 will determine the effectiveness of current design, procurement, and installation practices for mitigating losses related to the performance of nonstructural components and systems. Information obtained from Task NPP-12 will identify current practices that are deficient in mitigating earthquake losses and that should be changed to achieve enhanced nonstructural performance.

Under Task NPP-12, the Nonstructural Performance Products Team will direct a series of evaluations of buildings of different occupancies that have different nonstructural components with different levels of susceptibility to damage, and which are representative of current design and installation practices for the various regions of seismicity. Structural systems of various stiffness and strength levels, as well as damage-resistant systems such as seismic isolation and energy dissipation, will also be evaluated. Potential losses due to nonstructural component and system performance for a variety of shaking intensities will be evaluated, as will aggregate losses obtained by summing the projected loss at each intensity level factored by the probability of that intensity occurring. Evaluations will be performed for the same buildings assuming both rugged and fragile nonstructural systems and components. The difference in predicted performance relating to robust nonstructural procedures and standard nonstructural installation practices provide data on the effectiveness of current practice in mitigating losses and improving performance. Evaluation of the data will also allow the nonstructural components that contribute the most to losses to be identified.

These data will allow effective strategies to be developed for mitigating losses.

6.2.3 Identify Effectiveness of Alternative Strategies (NPP-13)

There are several potential alternative strategies for reducing the losses that result from damage to nonstructural components and systems. These include:

- For existing buildings, identifying those nonstructural components and systems, the upgrade/replacement of which could result in significant enhancement in building performance.
- Using contemporary approaches to seismic design, specification, and procurement of nonstructural components and systems, but significantly increasing the level of inspection, similar to that provided by California Office of Statewide Health Planning and Development (for hospitals), to ensure that systems and components are actually installed properly.
- Using more damage-resistant details for selected components and systems, such as installation of interior partitions in a manner that can better accommodate interstory drift.
- Adopting industrial-type design, procurement, and installation practices for the installation of vulnerable systems and components, such as piping systems. Under these practices, rather then requiring contractors to field-route piping, conduit, ductwork, and similar items and brace them using generic support specifications, the building design team would prepare routing plans for these systems that would indicate all required support and bracing locations and details. Inspection would be at a level comparable to that required for structural system construction.
- Using structural systems that minimize the demands on nonstructural components and systems, such as seismic isolation and energy dissipation.

Task NPP-13 will include study the cost effectiveness of each of these strategies, as well as others identified by the Nonstructural Performance Products Team. Information developed in Task NPP-13 will lead to practical and effective recommendations for improving performance by reducing losses resulting from nonstructural performance in the Seismic Performance Assessment guidelines.

6.2.4 Identify Preferred Strategies (NPP-14)

Using information obtained from Task NPP-13, Task NPP-14 will identify those strategies for mitigating damage to nonstructural components and systems that are most appropriate for achieving various performance objectives in various regions of seismicity. Inherent in this task is the realization that it is probably not necessary to use the same care in the installation of nonstructural components and systems in all buildings. For example, if nonstructural performance is found to be a relatively small contributor to the risk of casualties, but a significant contributor to economic loss relating to damage repair costs in moderate earthquakes, then strategies that minimize these costs would be identified based on the information obtained from Task NPP-13. The data from Task NPP-14 will be used to formulate recommendations contained in the Performance-based Design Guidelines.

6.2.5 Provide Input to Design Guidelines (NPP-15)

Task NPP-15 will develop the Performance-based Design Guidelines related to the design, procurement, installation, quality assurance, and maintenance of nonstructural components and systems in buildings of varying occupancies and for varying performance objectives. The Performance-based Design Guidelines will be formatted to present a menu of strategies for mitigating nonstructural-related losses, as appropriate to achieving different performance goals in regions of different seismicity. The guidelines will enable engineers to choose between specifying rugged installation of nonstructural components and systems, or selecting a structural system that minimizes demands on these components and systems and will consider the desired performance and seismic environment in which the building is constructed.

6.3 Phase 2 Risk Management Products Tasks

The Risk Management Products tasks will:

- Quantify the performance needs of various building stakeholder and decision-maker groups so that the best methods of expressing their needs can be identified.
- Explore how effective current and past building design and construction practices have been in meeting these needs.
- Develop decision-making tools and guidelines for decision-makers to assist them in selecting appropriate performance objectives as the design criteria for their buildings.

Much of the work of the Risk Management Products Team will consist of outreach to various stakeholder and decision-maker communities to determine the most important aspects of building seismic performance to them and how they prefer to conceptualize and quantify these performance issues. This will be followed by identified optimal or desired building performance objectives that are important to various stakeholders and decision-makers, considering the cost of mitigation.

Another major area of work will consist of exploring how well current and past practices in building design and construction meet the desired performance goals. Much of this work will be done by conducting performance evaluations of different case study model buildings that represent buildings of different occupancies, constructed in different eras, and located in different seismic environments to determine the losses associated with these buildings. In performing tasks related to defining the performance capability of current and past practices, the Risk Management Products Team will work closely with the Structural and Nonstructural Performance Products Teams, who will define the basis for consideration of performance in terms of identifying the typical structural and nonstructural environment of buildings of different eras and occupancies.

Finally, the Risk Management Products Team will develop a series of tools and guidelines that will assist decision-makers in selecting the appropriate performance goals for buildings of different occupancies. These tasks are described in greater detail in the following sections. Figure 6-3 presents a projected schedule for these tasks.

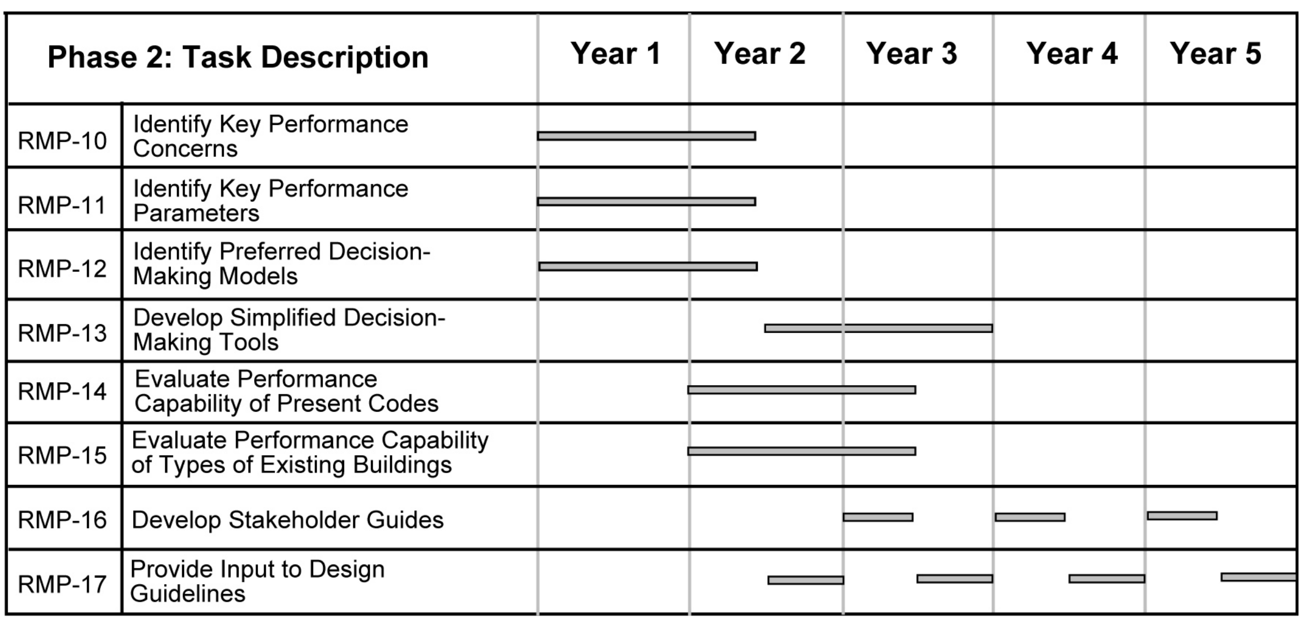


Figure 6-3 Phase 2: Schedule for Risk Management Products tasks.

6.3.1 Identify Key Performance Concerns (RMP-10)

Virtually everyone is a stakeholder in building seismic performance. Everybody lives and works in a building and therefore is at risk of personal injury or life loss if buildings are not adequately designed and constructed. Beyond this basic safety issue, individuals are at direct economic risk if their workplaces are damaged and their businesses unable to function. An indirect risk is disruption of a community's infrastructure that results in a general economic decline in a region. Earthquake damage can result in a general loss of housing, healthcare, and other essential services.

Despite the fact that nearly everyone's health and welfare makes them a building seismic performance stakeholder, relatively few can have direct affect, as decision-makers, on the seismic performance basis used to design and construct individual buildings. Building developers, building owners, building officials and some long-term building tenants are direct decision-makers in that they can direct design professionals to design or upgrade buildings to meet specific performance criteria. Property casualty insurers, mortgage lenders, corporations and commercial tenants, and the general public are indirect decision-makers. Typically, these groups cannot directly decide the criteria that design professionals will implement in design or upgrade of a facility; however, they can apply economic incentives to the decision-makers. Casualty insurers, for example, may offer preferential insurance premiums to buildings with certain performance characteristics, while declining to insure buildings with other characteristics. Mortgage lenders may similarly require that borrowers carry earthquake insurance on buildings with poor seismic performance attributes or choose not to make loans at all. Prospective building purchasers and tenants can affect the performance criteria selected by direct decision-makers by placing higher value in terms of purchase price and rent on properties that have superior seismic performance capability.

The amount of concern and influence these various indirect decision-makers have and exercise varies, depending on building occupancy, geographic region, and the likelihood that earthquakes will occur. In regions of high seismicity, for example, nearly all indirect decision-makers are sufficiently concerned with seismic performance issues to have some impact on the decisions made by the direct decision-makers. In regions of moderately high seismicity, a few indirect decision-makers (such as lenders or insurers) may affect decisions. In regions of low seismicity, however, not even direct decision-makers may make conscious consideration of seismic criteria.

In Task RMP-10, the Risk Management Products Team will hold a series of workshops and interviews with representatives of various decision-maker and stakeholder communities to determine the extent to which these communities have specific seismic performance concerns with buildings of different occupancies, and to identify what these concerns are and the strength of these concerns with regard to the community willingness to affect eventual decisions. This information will be used to guide direct decision-makers when making building performance decisions.

6.3.2 Identify Key Performance Parameters (RMP-11)

As described in Chapter 2, the primary measures of performance—the risks of casualties, direct financial loss related to damage repair and facility replacement costs and loss of occupancy or use of a building—can be expressed in a variety of formats, depending on the needs of the individual decision-maker. These include:

- Expected (median) value of the loss over a defined number of years.
- Average (mean) loss per year.
- Mean probability that losses would exceed a given level in a defined period of time.

In addition, it is possible to express the uncertainty associated with projection of these potential losses in a variety of formats. Some decision-makers do not like to make decisions considering uncertainty, but would rather make decisions based on maximum values or expected values. The confidence level associated with the loss projections could be explicitly stated, or the projected losses could be stated in terms of bounding conditions such as an expected value, and 10 percent and 90 percent confidence of nonexceedance values.

There is no unique best set of parameters to express these risks of loss and the associated confidence in the projections that will be preferable to all decision-makers or stakeholders. Lenders, for example, as an industry, have adopted Probable Maximum Loss as the preferred parameter for making choices on seismic performance. Probable Maximum Loss is an expression of the repair cost, at a 90% probability of nonexceedance, for earthquake shaking with a 10% chance of exceedance in 50 years. The insurance industry generally prefers to evaluate probable losses in terms of an average annualized loss that allows them to look at the probable losses to a large portfolio of insured properties on a uniform basis. Individual corporate risk managers and building owners often prefer to view losses in terms of the likely outcome given that a specific earthquake is experienced.

In this task, the Risk Management Products Team will hold a series of focused interviews with representative stakeholders and decision-makers to determine preferred parametric expressions of earthquake risk for use in making performance choices. This information will provide input to the development of Performance-Based Design Guidelines. It will also provide input into the formulation of Stakeholder Guides, developed by the Risk Management Products Team, and which will provide guidance to decision-makers on how to make appropriate building performance choices when developing, occupying, or upgrading buildings.

6.3.3 Identify Preferred Decision-Making Models (RMP-12)

Not all decision-makers will make building performance decisions in the same way. Generally, the decision will involve weighing the potential costs and benefits of obtaining improved seismic performance, then determining a level of investment that balances these costs and benefits, while also considering other potential uses of the funds. Many decision-makers will determine that seismic performance is not an important consideration worthy of the expenditure of funds, given other risks and needs that they face. For these decision-makers, the selection of an appropriate level of building performance is easy—they will select the minimum that regulatory authorities will permit. Other decision-makers, those who determine that seismic performance is a significant issue, may wish to perform a cost-benefit study that weighs the benefits to be gained from design for improved building performance against the costs of designing for it, and then select an optimum level of performance with respect to cost. Still other decision-makers may determine that certain building performance outcomes will result in total ruin of their enterprise, and will select performance objectives that reduce the risk of such ruin to an acceptable level, regardless of the cost involved.

In Task RMP-12, the Risk Management Products Team will meet with representative decision-makers and determine the typical decision-making processes used by different types of decision-makers. This information will be used to guide the development of simplified decision-making tools and the development of Stakeholder Guides.

6.3.4 Develop Simplified Decision Tools (RMP-13)

The basic Seismic Performance Assessment procedures described in Chapters 2, 3, and 4 express performance in terms of the risk of casualties, financial loss relating to repair and replacement of damaged buildings, and occupancy interruption. In Task RMP-13, the Risk Management Products Team will develop simplified cost-benefit approaches that decision-makers can use to determine appropriate performance objectives for a building, given their individual circumstances and risk tolerance. A number of simplified tools for performing such analyses have been developed. The California Seismic Safety Commission published a cost-benefit risk methodology, *Earthquake Risk Management: A Toolkit for Decision-Makers* (EQE, 1999), that allowed cost-benefit studies to be performed with information on the probable losses incurred for two levels of earthquake shaking. Porter (2004) presented a simplified methodology in which a cost-benefit analysis could be made based on estimated losses for a single level of earthquake shaking. Under Task RMP-13, the Risk Management Products Team will review these and other methodologies, including risk-of-ruin decision models, and select one or more simplified models for further development and presentation in the Stakeholders Guides.

Regardless of the specific cost-benefit model selected under Task RMP-13, an important consideration will be how to convert occupancy interruption time into financial loss. It is very difficult to do this on a general basis because the financial consequences of building occupancy interruption are dependent on the circumstances of the individual building occupants. The Risk Management Products Team will develop a simplified procedure to assist the decision-maker in identifying and quantifying the financial consequences of building occupancy loss so that these can be used in whatever decision-making process he or she prefers.

6.3.5 Evaluate Performance Capability of Buildings Conforming to Current Codes (RMP-14)

As noted earlier, many decision-makers will determine that the optimal level of seismic performance for their particular building investment is the minimum permitted by regulatory authority. Regulatory authorities typically rely on the building code to establish "acceptable" levels of building performance, even though the expected performance is poorly defined. In some cases, decision-makers who desire the minimum legally accepted performance may still wish to have buildings designed using a performance-based approach to determine if it will permit more economical designs or designs using systems or approaches that are not specifically permitted by the codes. In order to do this, it is necessary to quantify the performance of buildings designed and constructed in conformance with current building code requirements so the minimum acceptable level is clearly understood.

In Task RMP-14, the Risk Management Products Team will work with the Structural and Nonstructural Performance Products Teams to develop a series of representative case study buildings that represent typical structures designed and constructed in accordance with current code requirements and prevailing structural practices for various regions of seismicity and seismic use groups. The Risk Management Products Team will then evaluate the performance of these case-study buildings to define the performance provided by current code requirements. This will define the performance targets that will be used for the performance-based option of designing to minimum code criteria. This task will also allow a critical evaluation of the adequacy of current code provisions and design and construction practices, which will provide valuable information to the organizations responsible for development of building codes.

6.3.6 Evaluate Performance Capability of Typical Existing Buildings (RMP-15)

In past years, extensive work has been performed to identify types of existing buildings that pose an unacceptable risk to life. As a result of this past work, unreinforced masonry buildings, nonductile concrete frame buildings, tiltup building without adequate wall anchorage, and several other types of buildings have been identified as significant risks and building code requirements and ordinances for the upgrade of these structures have been developed adopted by some communities.

In the western United States, many seismic upgrades of existing buildings have been performed for economic reasons rather than reasons of protecting life safety. Lenders have commonly required seismic performance evaluations of buildings and adjusted the terms of loan agreements based on the results of these seismic assessments. Many building owners have consequently invested in voluntary upgrades of buildings in order to obtain more favorable mortgage loans. The evaluations performed on behalf of lenders typically estimate building Probable Maximum Loss, a measure of the probable repair costs for a building. Although many Probable Maximum Loss studies have been conducted of buildings, these have all been conducted on behalf of private parties and are not in the public domain. As a result, other than a subjective study performed by the Applied Technology Council in the mid-1980s (ATC, 1985)—which does not directly apply to many types of buildings constructed in the past 20 years—there is no comprehensive basis on which to rate the likely economic losses associated with buildings of different types and eras of construction.

In Task RMP-15, the Risk Management Products Team will develop Seismic Performance Assessments for a number of existing building types located in a variety of seismic environments. Data on the likely repair costs and occupancy interruption times will be obtained for different types of buildings. Task RMP-15 will provide data for the Stakeholder Guides on the approximate seismic risk associated with different types of existing buildings. Risks will be expressed in terms of life risk, repair cost risk, and occupancy interruption risk. This will enable decision-makers to develop rapid understanding of the probable level of risk associated with different buildings and to determine if more detailed consideration of an existing building for a given use is appropriate.

It is anticipated that this task will be performed by a number of consultants around the United States, working under the direction of the Risk Management Products Team. These consultants will be asked to select representative buildings in their region and to perform evaluations of these buildings. This data will be compiled into a database by the Risk Management Products Team.

6.3.7 Develop Stakeholder Guides (RMP-16)

The Stakeholder Guides will provide information to decision-makers they can use to make performance choices for buildings they develop or occupy, and assist them in making appropriate seismic performance choices when entering into building design or occupancy projects. Since there are many different types of decision-makers with different needs, interests, and levels of sophistication, a series of publications will be prepared, each with a different intended primary audience. On a preliminary basis, guidelines will be developed for the following decision-maker groups:

- Building developers
- Corporate risk managers
- Mortgage lenders
- Property casualty insurers
- Institutional risk managers
- Homeowners
- Small business owners

Publications will be tailored to the individual interests, decision processes, and levels of sophistication of the target stakeholder group. Focus groups of representative stakeholders in the individual areas will be asked to review the publications in draft form and provide input as to whether the publications have the appropriate focus and how useful they are. At least two preliminary drafts will receive outside review. Final development of the Stakeholder Guides will be tailored based upon this feedback.

6.3.8 Provide Input to Design Guidelines (RMP-17)

The primary goal of Task RMP-17 is to develop Performance-based Seismic Design guidelines that will help design professionals to efficiently develop designs that will be able to meet a broad range of performance objectives.. The Risk Management Products Team will be responsible for developing those portions of the Performance-based Design Guidelines that relate to the basic performance-based seismic design process, selection of appropriate performance objectives for buildings, communications with decision-makers and consideration of alternative strategies, and all other structural and nonstructural measures to mitigate losses. It is anticipated that much of the quantitative material contained in the Stakeholder Guides, developed under Task RMP-16, will be included in the Performance-based Design Guidelines, so that design professionals can work effectively with decision-makers and help them select appropriate performance goals for projects.

The community of practicing engineering design professionals will provide significant input to of these documents, and opportunities will be provided for public input as well. During the second year of the Phase 2 Program Plan, this draft will be prepared for internal team coordination and planning only, and will not be released for public review. Second and third drafts of the publication will be prepared in the third and fourth years of Phase 2, and public review of these documents will be solicited. The final draft, prepared in the fifth year, will address the public review comments obtained in prior review cycles.

Appendix A

Seismic Performance Assessment

The next-generation performance-based seismic design guidelines will measure building performance in terms of the potential for casualties, repair/replacement costs and downtime resulting from earthquake-induced damage to a building. Section 2.5 of this report introduced the basic concepts behind expressing performance in this manner and the basic steps in the performance-based design and assessment process. This Appendix A provides a more detailed introduction to these concepts, which are still at a preliminary level of development. Its primary focus is on the framework for calculating probable future building performance and expressing this performance in a flexible format to suit various decision-makers. Appendices B and C present several approaches that have been developed on a preliminary basis, to implement these procedures. More detailed development of these approaches will be conducted under the project described in this Program Plan.

A.1 Performance-Based Design Process

Figure A-1 illustrates the basic performance-based design process, previously introduced in Section 1.3 and discussed in Section 2.5.

The process begins with the selection of design criteria stated in the form of one or more performance objectives. Performance objectives are statements of the acceptable risk of incurring different levels of damage and the consequential losses that occur as a result of this damage. In the next-generation performance-based design procedures, performance objectives are statements of the acceptable risk of incurring casualties, direct economic loss (repair costs), and occupancy interruption time (downtime) associated with repair or replacement of damaged building elements. These performance objectives can be stated in three different ways:

- *Intensity-based objectives* – statements of the acceptable casualties, repair/replacement costs and downtime in the event that the building is subjected to a specific intensity of ground shaking
- *Scenario-based objectives* – statements of the acceptable casualties, repair/replacement costs and downtime if a specific earthquake event occurs, where the event is defined by a magnitude, fault, and possibly, rupture location and/or direction

- *Time-based objectives* – statements of the acceptable probability of incurring casualties, repair/replacement costs and downtime, over a defined period of time, considering all possible earthquake events that can occur and the probability of occurrence of each, within the defined time frame.

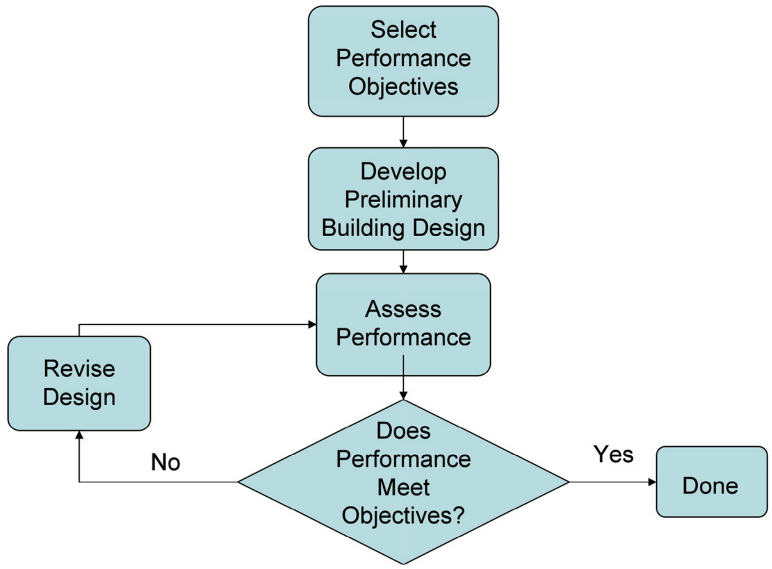


Figure A-1 Performance-based design flow diagram.

Once design criteria in the form of performance objectives have been selected, the next step in the process is the development of a preliminary design. This includes selection of a site, specification of the building configuration and occupancy, selection of structural systems, and definition of the types and quality of various nonstructural components and systems and their locations throughout the structure. Phase 2 of this Program Plan addresses the action items necessary to develop guidelines to assist engineers in developing preliminary designs likely to meet desired performance objectives.

Once performance objectives have been selected and a preliminary design developed, it becomes necessary to assess the performance capability of the design to determine if it meets the selected performance objectives. Detailed performance assessment procedures, and guidelines to assist design professionals with this process, will be developed in Phase 1 of this Program Plan. The following sections of this Appendix describe in some detail the basic concepts associated with the performance assessment process and some of the issues that need to be resolved during implementation of Phase 1 of this Program Plan.

A.2 Performance Assessment Process

Figure A-2 illustrates the individual steps in the performance assessment process, as it will be implemented in the next-generation performance-based seismic design procedures. These steps include:

- Characterization of the ground shaking hazard.
- Analysis of the structure to determine its probable response and the intensity of shaking transmitted to supported nonstructural components as a function of ground shaking intensity.
- Determination of the probable damage to the structure at various levels of response.
- Determination of the probable damage to nonstructural components as a function of structural and nonstructural response.
- Determination of the potential for casualty, capital and occupancy losses as a function of structural and nonstructural damage.
- Computation of the expected future losses as a function of intensity, structural and nonstructural response, and related damage.

These steps are discussed in the sections that follow.

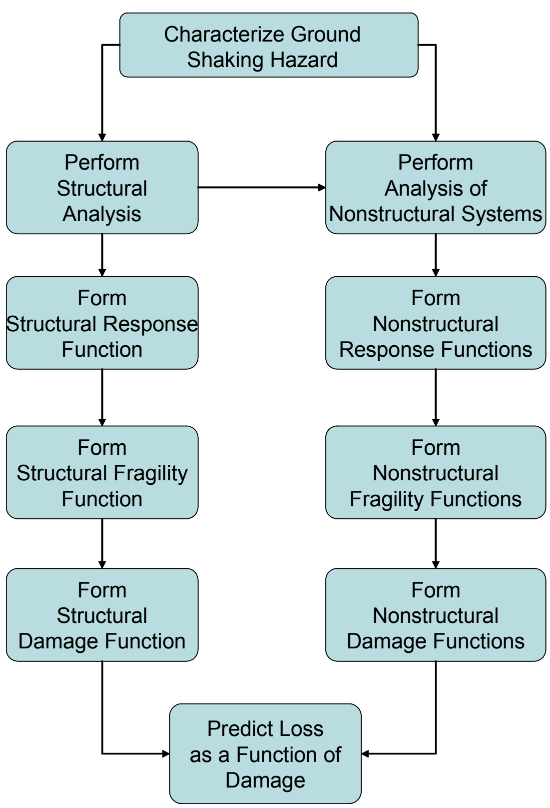


Figure A-2 Performance Assessment Process

A.3 Characterization of Ground Shaking Hazard

The way that ground shaking is characterized in the performance assessment process is dependent on the type of performance objective, (i.e., intensity-based, scenario-based or time-based) that is being used. The simplest form of ground shaking characterization occurs when intensity-based performance objectives are used. In this case, it is only necessary to define a specific intensity of motion that the building will be designed to resist.

The parameter used to describe ground motion intensity is termed an intensity measure. A number of different intensity measures have been used in the past, including Modified Mercalli Intensity (MMI), Rossi-Forrell Intensity, peak ground acceleration, and spectral response acceleration, among others. For more than 30 years, design procedures have used linear acceleration response spectra and parameters derived from these spectra as the basic intensity measures. Linear acceleration response spectra are useful and form the basis for both present national seismic hazard maps and building code procedures. However, there is presently a lack of consensus as to how to derive and scale ground motion records so that they appropriately match the intensity represented by a response spectrum. Further, most current procedures for ground motion record scaling produce significant variability in predicted response when nonlinear dynamic analyses are performed. An important task under Phase 1 of this Program Plan is to provide guidance on selection and scaling of records for purposes of analysis, so as to minimize the variability associated with response prediction.

In order to assess the ability of a structure to meet a scenario-based or time-based performance objective, it is necessary not only to define a single intensity of motion, but rather, a range of motion and intensities, and the probability of occurrence of each. This information is typically presented in the form of a hazard function. The hazard function for a site is simply an expression of the probability that ground shaking of different intensities may be experienced at the site. The hazard function can be formed on a scenario basis (considering only the occurrence of a specific magnitude earthquake on a specific fault) or on a time-period basis (considering all potential earthquakes on all known faults and the probability of occurrence of each within a defined period).

Figure A-3 is an example scenario-based hazard function for a hypothetical building site and earthquake scenario—for example, a magnitude-6.5 earthquake on a fault that has a closest distance to the site of 20 kilometers. This function indicates, in the form of a log-log plot, the conditional probability that ground shaking with a peak ground acceleration exceeding various levels will be experienced at the site, given that this scenario earthquake occurs. Figure A-4 presents this same hazard function, plotted in a Cartesian rather than logarithmic scale.

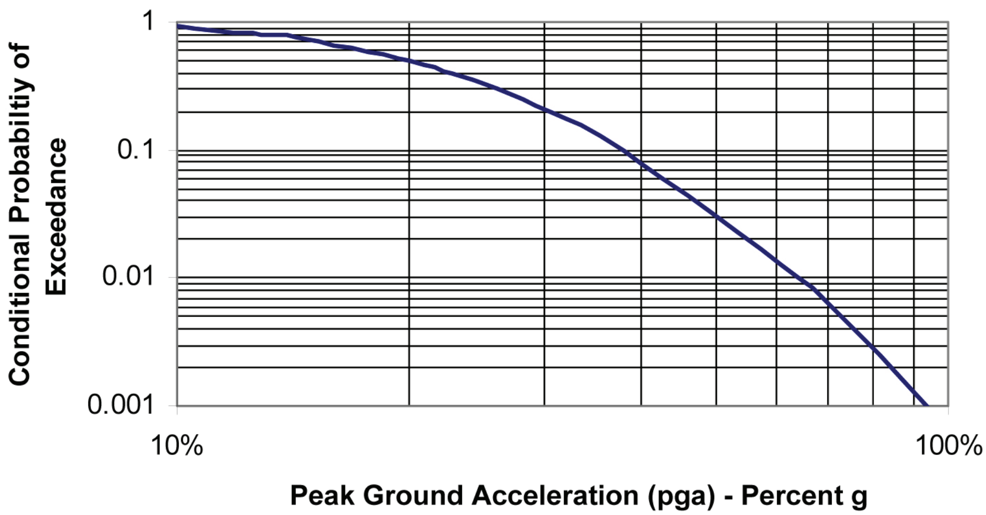


Figure A-3 Scenario-based hazard function for hypothetical building site and earthquake scenario.

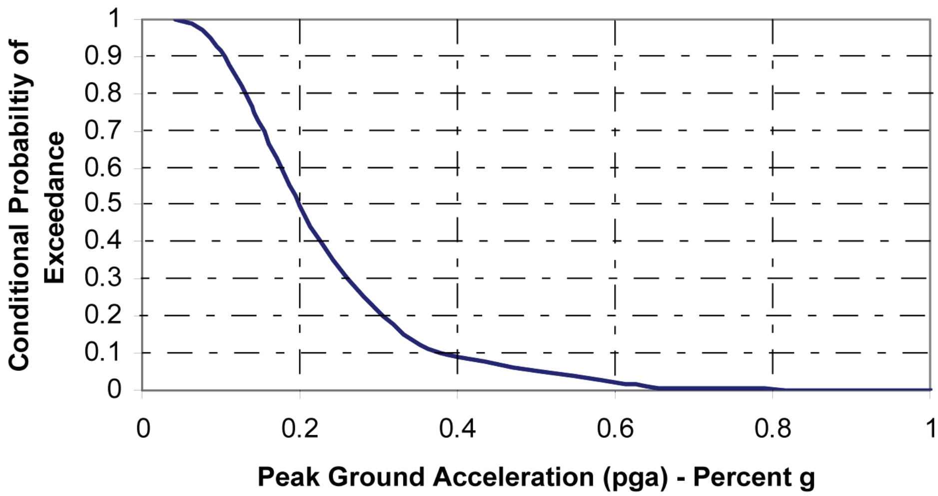


Figure A-4 Scenario-based hazard function for site using Cartesian coordinates.

As can be seen, this hazard function indicates a 50 percent chance that the peak ground acceleration produced at this site from the scenario earthquake will have a value in excess of 20 percent g, a 25 percent chance that it will have a value in excess of 40 percent g, and approximately a 5 percent chance that it will have a value in excess of 60 percent g. Such uncertainty as to the actual value of ground shaking intensity that will occur at a site given that a scenario earthquake occurs is a result of a number of factors, described below.

Hazard functions are most commonly generated using attenuation equations. Attenuation equations are empirically derived functions that relate various ground motion intensity measures, such as peak ground acceleration, to parameters that are descriptive of the earthquake and site, including the magnitude of the earthquake, the type of fault mechanism, the distance from the rupture surface to the site, the type of soil conditions present at the site, the direction in which the fault rupture propagates, and other factors. The attenuation equations are developed by performing regression analyses of actual strong ground motion recordings against these various parameters. While the engineering parameters have significant correlation with the recorded data, they do not correlate perfectly, resulting in scatter of the actual data on ground shaking intensity relative to the values predicted by the equations. For example, the 2004 Parkfield California earthquake occurred in an area of dense instrumentation, and demonstrated that earthquakes can have a surprising variability in ground motion intensity over short distances.

Additional variability is introduced by the random nature of earthquake occurrence: a fault may rupture at any point along the fault; and it may either rupture towards or away from the site. Still more variability is introduced by a lack of precise knowledge about the site soil conditions, the presence of sedimentary basins that could cause reflection of the earthquake waves, or the response characteristics of hilly terrain, all of which can affect shaking intensity.

When time-based performance objectives are used, ground shaking intensity is represented by hazard functions that are developed considering all potential earthquake scenarios, and the probability of occurrence of each scenario within a given period of time. Time-based hazard functions appear similar to scenario-based hazard functions and are used in the same way. However, rather than indicating the conditional probability of experiencing different levels of shaking intensity given that a specific scenario earthquake occurs, probabilistic hazard functions indicate the total probability of exceeding different shaking intensity levels at a site over a defined period of time. Hazard function may express the probability in the form of an annual probability of exceedance (or nonexceedance), an average return period, or the probability of exceedance (or nonexceedance) in a defined period of years, usually taken as 50. It can be expressed as a mean probability, in which the uncertainty associated with the function is averaged, or confidence bounds associated with the uncertainties can be expressly indicated.

A.4 Structural Analysis and Structural Response Functions

Structural analysis serves two basic functions in the performance assessment process:

- Prediction of structural response quantities, including member forces, deformations, and interstory drifts that can be used as predictors of the damage sustained by the structure. These response quantities are termed *engineering demand parameters*, or *demands*.
- Prediction of the intensity of demands on nonstructural elements and systems supported by and suspended from the structure. These demands include interstory drifts, floor accelerations, and velocities and are termed *nonstructural engineering demand parameters*, or *nonstructural demands*.

The first use of structural analysis is to predict structural damage. For a given structure and a given level of ground motion intensity, structural analysis is performed to predict the value of one or more demands. In a later step of the performance assessment process, these parameters will be used to predict damage. In order to illustrate this process, we consider the case of a hypothetical, three-story, moment-resisting steel frame structure located on an arbitrary site.

As previously discussed, in order to assess the performance of this hypothetical structure, or any structure, ground motion intensity must be quantified with the use of an intensity measure. For the purpose of this illustration, the 5 percent-damped, elastic spectral response acceleration at the fundamental period of the structure is selected as the intensity measure. Interstory drift is selected as the demand used to predict damage. A ground motion record that is representative of the character of shaking likely to be experienced at the site is selected and appropriately scaled so that it corresponds to a particular value of the 5 percent-damped spectral response acceleration. Next, a nonlinear dynamic analysis of the structure is performed using this scaled record and the peak value of the interstory drift at each level is determined.

The value of interstory drift predicted by the analysis depends on several factors, including the distribution and magnitude assumed for the structure's mass, the stiffness, strength, damping, and hysteretic characteristics used to model the structure as well as the specifics of the ground motion record. If a different ground motion record is selected for the analysis and is appropriately scaled to the intensity measure, and all of the other modeling parameters are left unchanged, a different value for the interstory drift will likely be predicted. In general, if this process is repeated using a number of different ground motion records, all scaled to the same value of the intensity measure, each will result in somewhat different predictions of peak interstory drift. If a large number of these ground motion records are used in the analysis and each is equally representative of the intensity measure and the hazard for the site, then the results of these various analyses will define a random distribution of interstory drift demands that can result from this particular ground motion intensity level. Figure A-5 is a probability density function representing such a distribution.

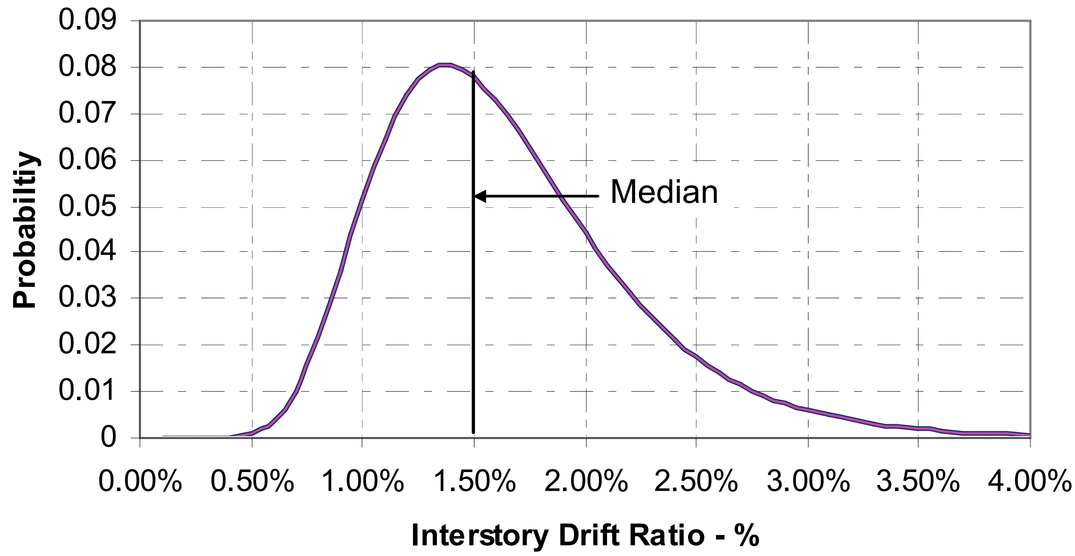


Figure A-5 Probability distribution for structural response, expressed as interstory drift ratio for a particular structure and ground shaking intensity.

The information presented in Figure A-5, can also be represented in the form of a cumulative probability function, which indicates the probability that interstory drift will be less than or equal to a given value. Figure A-6 presents this same data shown in Figure A-5 as a cumulative probability function.

For the particular distribution illustrated in Figures A-5 and A-6, the median value is an interstory drift of 1.5%. That is, there is a 50% chance that the interstory drift resulting from any ground motion for this site corresponding to this intensity level will produce a drift less than 1.5%. The distribution is somewhat skewed, as is typical of such distributions. The average (mean) value is an interstory drift of about 1.6%. There is a 10% probability that interstory drift resulting from ground motions at this intensity level will be less than 1% and a 90% chance it will be less than 2.3%.

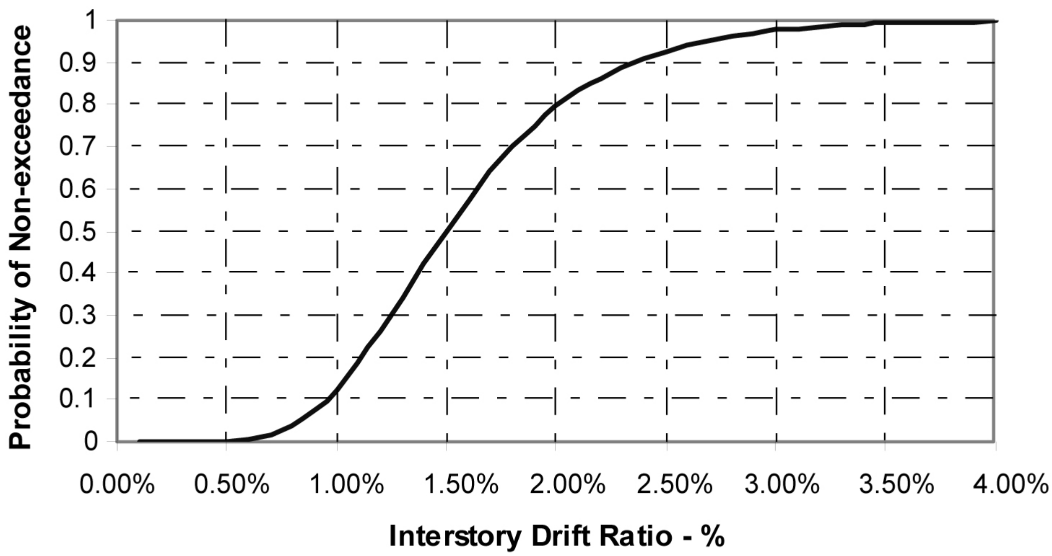


Figure A-6 Cumulative probability distribution for structural response expressed as interstory drift ratio for a particular structure and ground shaking intensity.

If similar analyses are performed for a range of ground motion intensities, it is possible to develop a structural response function that indicates the probable distribution of the demand, in this case interstory drift, for different levels of ground motion intensity. Figure A-7 illustrates a structural response function of this type, indicating the probable range of interstory drift for different levels of first mode elastic spectral response acceleration for a hypothetical structure. The figure shows the median prediction of interstory drift demand as well as interstory drift demands at 10% and 90% probabilities of exceedance, for various spectral function, similar to that of Figure A-5, that fits these data. In Figure A-7,

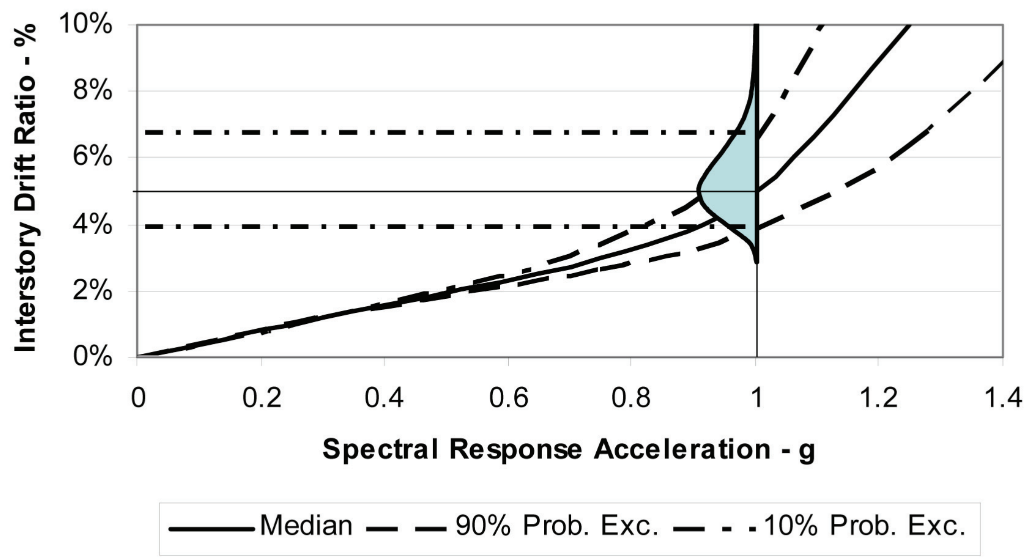


Figure A-7 Hypothetical structural response function for building.

such a probability density function is overlaid on the response function at a acceleration values. As illustrated in the figure, at any spectral response acceleration level, S_a, it is possible to superimpose a probability density value of first mode spectral response acceleration of 1g. It can be seen that the median value of the predicted demand is an interstory drift ratio of about 5%, the 90% probability of exceedance interstory drift ratio is about 3.8%, and, the 10% probability of exceedance interstory drift is about 6.4%. It can also be seen that the amount of variability in potential response is negligible at low ground motion intensity levels, where structural response is linear and increases rapidly as ground motion intensity increases and response becomes nonlinear.

The structural response function illustrated in Figure A-7 was developed with the stiffness, mass, damping, and hysteretic parameters for the structure held invariant, as if the true value of these parameters was precisely known. While most probable values for these parameters can be estimated with ranges of potential variation, the true values are seldom, if ever, known, and there is some uncertainty as to what the precise values are. To the extent that the values for the parameters used in the analyses are inaccurate, the resulting structural response function for the building may either over- or under-predict the probable response level at a given ground motion intensity level.

If an additional series of analyses of the structure are performed, varying the assumed values for the uncertain structural parameters—including mass, stiffness, strength and damping—within their likely limits, it would be possible to predict the additional variation in probable interstory drift demand introduced by these uncertainties. The effect of these uncertainties will be to broaden somewhat the scatter associated with the response function and produce some non-negligible variation in predicted response even at low levels of ground motion intensity, where the structural response is linear.

For a real structure, the task of defining the response function, considering these uncertainty bounds, can be a complex and time-consuming process requiring many analyses. As an alternative, it is possible to estimate the additional scatter introduced by the uncertainties by assuming that the variability can be represented by a standard distribution shape, typically log-normal, and by selecting a coefficient of variation based on either expert judgment or the variability observed in analysis of a limited number of standard structures. The development of efficient and practical methods of developing such response functions for routine use on engineering projects will be an important part of Phase 1 of this Program Plan.

The second purpose of structural analysis is to predict the probable intensity of shaking that will be experienced by nonstructural components and systems mounted at different levels in the structure. These data will typically be developed and represented in a form similar to the response function illustrated in Figure A-7, except that in addition to interstory drift, other parameters that are useful to the prediction of nonstructural component response (such as in-structure response acceleration at a particular nonstructural component period) will also be used.

A.5 Formation of Nonstructural Response Functions

If a nonstructural component is infinitely rigid, the shaking imparted to the component by the structure, expressed in the form of peak interstory displacement or floor acceleration, can be used directly to predict the behavior of the component. However, nonstructural components with finite rigidity will have their own dynamic response to the motions imparted to them by the structure. For such components, it may be necessary to perform a structural analysis of the component to predict its response to the shaking imparted to it (in the form of nonstructural demands, such as acceleration or displacement of the component itself), which can then used to assess the level of damage incurred.

Figure A-8 is illustrative of a nonstructural component demand function that could be used to predict the response of a flexible component having a period of 0.5 second that is sensitive to acceleration. In Figure A-8, in-structure response acceleration at a period of 0.5 second, that is, the

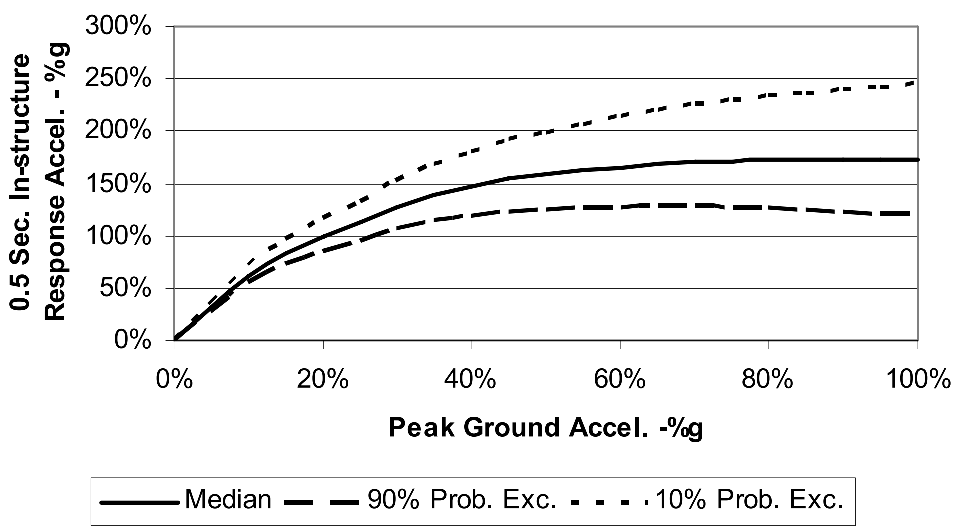


Figure A-8 Illustrative nonstructural component demand function for floor response acceleration at 0.5 second.

acceleration experienced by a component having a natural period of vibration of 0.5second, mounted at a particular level in the structure, is plotted as a function of ground motion intensity, here represented by peak ground acceleration. As with the structural response function of Figure A-7, uncertainty and confidence bands are an integral part of such a plot.

In order to be useful in the performance assessment process for nonstructural components, it is necessary to convolve the data in the demand function with the ground shaking hazard function for the site. This process yields a hazard function that indicates the probability of experiencing a given intensity of in-structure shaking at a particular floor or roof level. Figure A-9 illustrates such an in-structure shaking intensity function, which has been constructed by convolving the demand function of Figure A-8 with the hazard function of Figure A-3. The resulting in-structure shaking hazard function of Figure A-9 could be used to predict the response of nonstructural components with a fundamental period of 0.5 second mounted at the particular level of the hypothetical building used in this example. A family of such curves for different nonstructural component periods could then be used to develop response functions for various nonstructural components, in the same way response functions were developed for the structure itself.

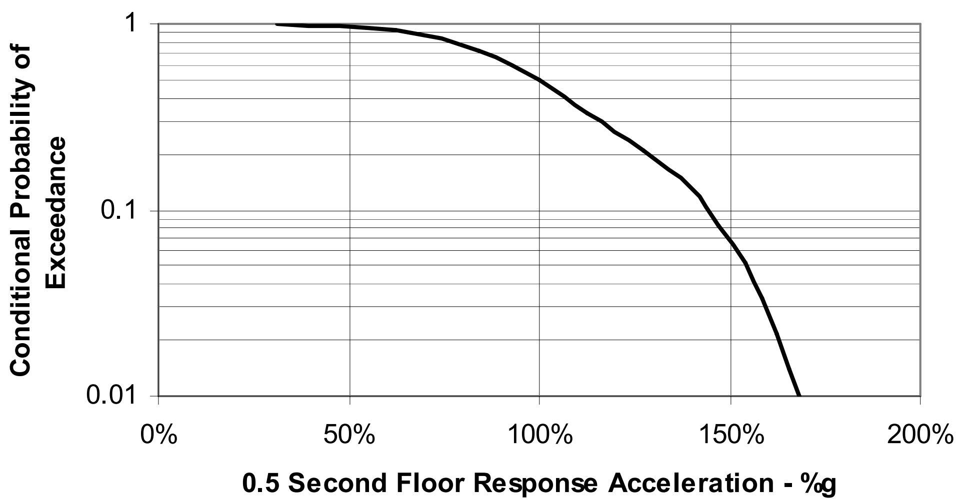


Figure A-9 Illustrative nonstructural component response acceleration hazard curve.

A.6 Evaluation of Structural Fragilities

Structural fragilities are functions that indicate the probability that a structural component or system will experience damage greater (or less) than a certain level, given that the component or system experiences a certain level of response, as measured by the demand. As is the case with response functions, fragilities are expressed as probability distributions, rather than deterministic relationships in order to account for the variability and uncertainty inherent in the process of predicting structural damage as a function of structural response.

The variability is associated with such factors as the random nature of structural response to individual ground motion records and the inability of simple demand parameter to distinguish between this response variation and the damage it causes. For example, two different ground motions may each produce peak interstory drift demands of 4 inches in a structure. However, one of these ground motions may cycle the structure to this drift level one time, then restore the structure to small oscillations about its original position; while the second ground motion may cycle the structure to this drift level several times and leave the structure displaced nearly to this level. Clearly the second motion will be more damaging to the structure than the first motion, though the value of the demand is the same. Such effects are not predictable unless the precise ground motion and structural response is known, which will never be the case. Uncertainty is introduced through such factors as lack of precise definition of material strength and construction quality.

In order to form fragility functions, it is first necessary to establish measures of damage. A variety of such measures are possible. Early research in this area used the concept of damage indices as measures of damage to structural elements and systems. Damage indices are non-dimensional parameters, typically having values in the range of 0 to 1 where a value of 0 would indicate no damage and a value of 1 would indicate total damage. Most such damage indices have been developed on an element or component basis, but a few have been calculated on a global structural level. Generally, these damage indices are specific to a particular type of structural component or structural system. Most are of the form:

$$DI = \left(\frac{\Delta_i}{\Delta_u}\right)^x + \left(\frac{E_i}{E_u}\right)^y \leq 1.0 \qquad \text{(A-1)}$$

where the quantity (Δ_i/Δ_u) is the ratio of the maximum inelastic displacement or deformation demand induced in the structure (or component) by the ground shaking to the ultimate static displacement capacity of the structure; and the quantity (E_i/E_u) is a measure of cumulative damage resulting from repeated cycles of inelastic response and has most commonly been expressed in the past as a ratio of inelastic energy dissipation demand to capacity. These damage indices have not been widely used for several reasons, including:

- They require the use of nonlinear response history analysis, a complex analysis procedure not widely used in practice.
- The energy component is typically a small part of the computed index, making the complexity introduced by the second term seem unjustified.
- There is little research available to suggest appropriate values of the E_u term.
- Engineers have little intuitive feel for damage indices and have difficulty relating them to an understanding of a structure's actual performance.

A second method for assigning damage parameters used in the past was to assign a series of discrete damage states or ranges, representing progressively more severe states of damage. This is the approach taken both by present-generation performance-based design methodologies, such as FEMA 356, and also by loss estimation methodologies such as HAZUS. In FEMA 356, these damage states are termed the Operational, Immediate Occupancy, Life Safety, and Collapse Prevention performance levels, with Operational representing a state of negligible damage and Collapse Prevention a state of near-complete damage. The HAZUS methodology uses damage states termed Slight, Moderate, Severe, and Complete, assigned based on the analyst's understanding of the extent of damage to the structure as predicted by analysis. It should be possible for particular structural systems to develop relationships between either the FEMA 356 performance levels or HAZUS damage states and computed damage indices. However, it is not clear that either the damage indices, or the standard performance levels of the first-generation procedures, can be used efficiently to predict repair costs, time out of service, or potential life loss.

A third potential method of parameterizing damage consists of a direct tracking of the condition of individual structural elements and components, on a piece-by-piece basis, coupled with measures of building-wide damage. For example, for moment-resisting steel frames, damage measures that could be used on a connection-by-connection basis include: panel zone yielding, beam plastic hinging, beam flange buckling, and welded joint fracturing. Measures of building-wide damage could include tracking of residual interstory drifts of different amounts on a story-by-story basis (e.g., 1 percent, 2 percent, 3 percent, etc. up to collapse). Each of these damage states would have different implications with regard to occupant safety during the earthquake, post-earthquake safety, repair effort and cost, and occupancy interruption. The consequences of each of these individual damage measures must be aggregated on a system basis, over the entire structure.

Structural fragilities may be formed on either a structure-specific or structural system-specific basis. Absent a practical ability to build prototype structures, test them, and measure the amounts of damage that have occurred, fragilities must be formed on the basis of simulation or analysis, laboratory data on component performance, and expert judgment. As an example, fragilities have been constructed on a preliminary basis for moment-resisting steel frames based on data obtained from the FEMA/SAC program completed several years ago. For the purpose of this example, fragilities have been developed for the case of a regular, low-rise special moment resisting steel frame building employing reduced beam section detailing. Local damage measures relating to the condition of individual structural components are taken as initiation of beam yielding, initiation of beam flange buckling, and beam flange fracture. Building-wide damage measures, relating to the condition of the overall structure are taken as permanent interstory drifts of 1 percent, 2 percent, 3 percent and story collapse.

Following recommendations from the FEMA/SAC project, a single demand, peak interstory drift ratio, is used as an index for each of these damage measures. Based on the FEMA/SAC study, median values of interstory drift demand at which beam flange yielding initiates is taken as 0.01 radians; at which beam flange buckling initiates as 0.02 radians; and at which beam flange fracture initiates as 0.06 radians. A best "estimate" of permanent interstory drift is 50 percent of peak interstory drift, and a best estimate of the interstory drift at which collapse initiates is 0.1 radians. Coefficients of variation associated with each of these behaviors are estimated at 0.1 for initiation of yielding, 0.2 for initiation of buckling, 0.3 for initiation of flange fractures and permanent interstory drift, and 0.5 for initiation of collapse.

Figure A-10 shows a plot of fragilities for these several damage states for individual beam-column connections. Figure A-11 shows a plot of fragilities for global measures of damage for this structural system computed using the above data and assumptions. In order to construct these fragilities, it has been assumed that the distribution of failure capacities is log-normally distributed using the median values and variances described in the previous paragraphs.

The fragility curves illustrated in Figures A-10 and A-11 indicate the probability that damage will be equal to or greater than that corresponding to each of the several damage states. To determine the probability that a structure will experience damage within a given state at a given level of response, it is necessary to take the difference between the probability that it initiates damage within the given state and the probability that the structure will initiate damage in the next most severe state. For example, for the fragility curves plotted in Figure A-10, at an interstory drift demand of 3 percent, there is essentially a 100 percent chance that beam flanges will have yielded, approximately a 95 percent chance that buckling damage will initiate in flanges, and approximately a 5 percent chance that damage will include fracturing of the beam flanges or welded connections. For this case, the probability that beam flanges will have yielded but not buckled will be the probability of yielding (100 percent) minus the probability of buckling (95 percent), or 5 percent. The probability of buckling but not fracturing will be the probability of buckling (95 percent) minus the probability of fracturing (5 percent), or 90 percent.

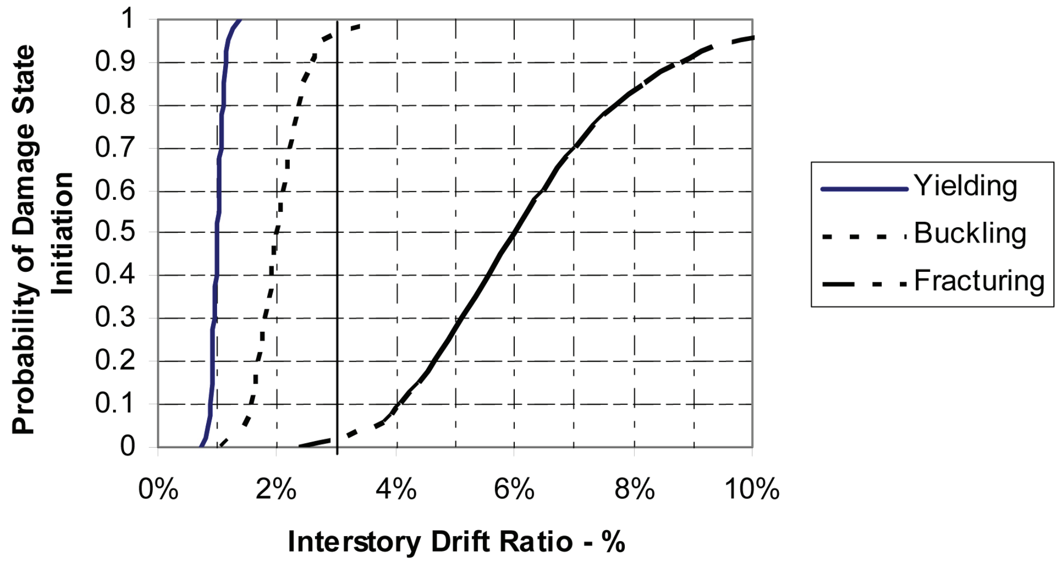


Figure A-10 Example fragility function for beam-column connection behavior.

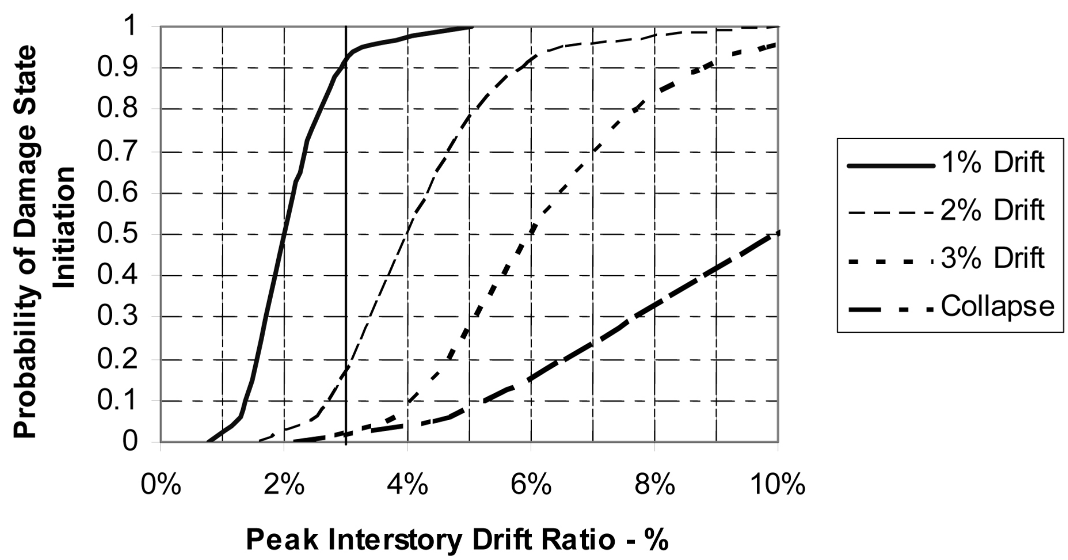


Figure A-11 Example fragility function for building-wide structural behavior.

Similarly, at a peak interstory drift demand of 3%, there is a 96% probability that the structure will sustain a permanent interstory drift of 1% or greater, an 18% chance the structure will sustain an interstory drift of 2% or greater, approximately a 5% chance of a permanent interstory drift of 3% or greater, and about a 3% chance of collapse.

A.7 Development of Nonstructural Fragilities

Nonstructural fragilities serve the same purpose as structural fragilities, except that they indicate the probability that nonstructural components or systems, rather than structural components or systems, will be at or in excess of given damage levels. For rigid components, the fragility can be formulated as a direct function of a structural demand, such as interstory drift or peak floor acceleration. For flexible components, the fragility will be a function of the response of the nonstructural component, as measured by nonstructural demands obtained from structural analysis of the nonstructural component. Damage states that may be meaningful for nonstructural components and systems could include loss of function, loss of leak-tightness, loss of structural integrity, and toppling, as well as others. In general, each class of nonstructural component or system, such as suspended ceilings, fire sprinkler systems, interior partitions etc., will have different fragility functions, which will be tied to several different damage states and intensity measures. These can be determined through collection of earthquake performance data on damage sustained by actual installations, through laboratory testing programs, and in some cases, through structural analysis, just as would be done for the building structure itself.

Figure A-12 is a hypothetical fragility curve for a single drift-sensitive nonstructural component (exterior curtain walls). This fragility curve shows the probability of experiencing various damage states including: breakage of glass, fallout of glass, and failure of panel connections as a function of structural interstory drift. The fragilities shown in Figure A-12 are illustrative only and are not representative of real data.

In addition to fragility functions for nonstructural components, it is also necessary to develop fragility functions for nonstructural systems such as fire sprinklers, building lighting, HVAC systems, manufacturing systems, data processing systems, etc. In order to develop fragility functions for such systems, it is necessary to consider the inter-relationships between the components that comprise the system and understand how failures of individual components and combinations of components affect system performance. Typically, it will be necessary to construct logic trees to identify the effect of the failure of single components and combinations of components on system operability and function. Then, at various levels of intensity, the failure probability for the individual components, for combinations of components, and for the system itself can be calculated, allowing a system fragility to be developed.

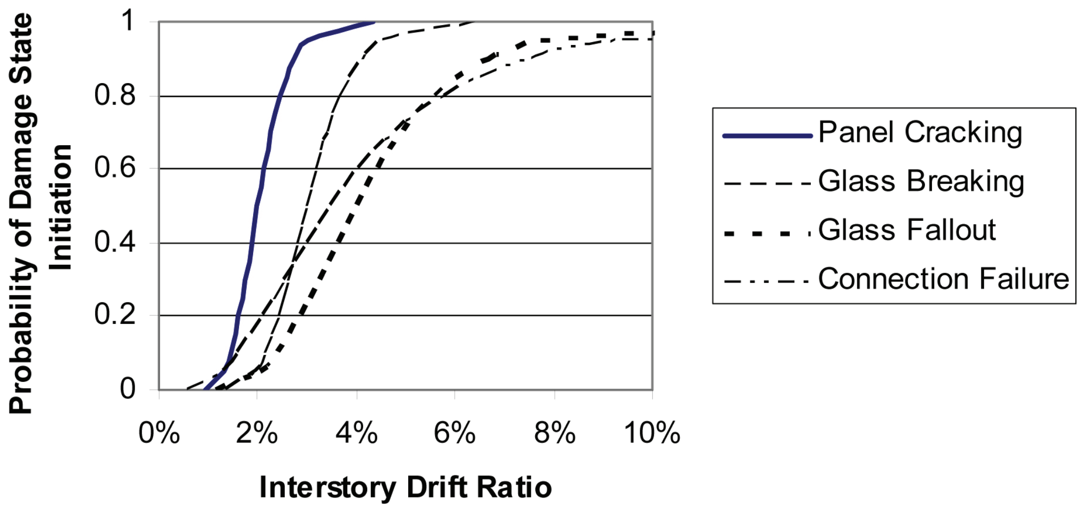


Figure A-12 Hypothetical fragility curve for exterior cladding.

A.8 Evaluation of Structural and Nonstructural Loss Functions

Loss functions indicate the probability of incurring various levels of loss, given that a structural or nonstructural component or system is damaged to a given level. Loss functions are expressed in parameters such as casualties, direct economic loss (repair costs), and/or hours of lost service or occupancy (downtime). Loss functions can be constructed for a given building or class of buildings by postulating damage to the structure (or nonstructural component/system) that is representative of a damage level for which there is an available fragility function, and estimating the losses associated with this damage. By varying the assumptions, or exploring the level of uncertainty associated with the assumptions inherent in these estimates, it is possible to determine probability distributions of the possible losses, as a function of the damage states. Alternatively, it may be possible to construct loss functions directly from historical earthquake data, if available.

Loss functions tend to incorporate significant uncertainty as compared with hazard, response, and fragility functions. This is because they are highly dependent on human factors. These include the owner's ability to act rapidly in retaining the necessary design professionals and construction contractors to effect repairs, the efficiency with which the design professionals and contractors operate, the speed with which city and/or county building departments approve proposed repair programs, and the willingness of people to occupy the building during repair—among other factors.

Figure A-13 is a hypothetical loss curve that indicates the probable repair cost for a single beam-column connection in a moment-resisting steel frame structure if the connection is damaged to any of the levels indicated in Figure A-10—that is, beam flange yielding, beam flange buckling, or beam flange fracturing. For example, Figure A-13 shows that if a connection is damaged to an extent that the welded beam flange to column flange fractures, there is roughly a 20% chance that repair cost will be $1,400 or less, a 50% chance the repair cost will be $5,000 or less, and an 80% chance the repair cost will be $17,000 or less. This variability in the potential repair cost is a result of such factors as the type of ceiling present, the amount of ductwork and other utilities that restrict access to the damaged framing, the type of fire-resistive materials present, and the efficiency of the contractor in making repairs.

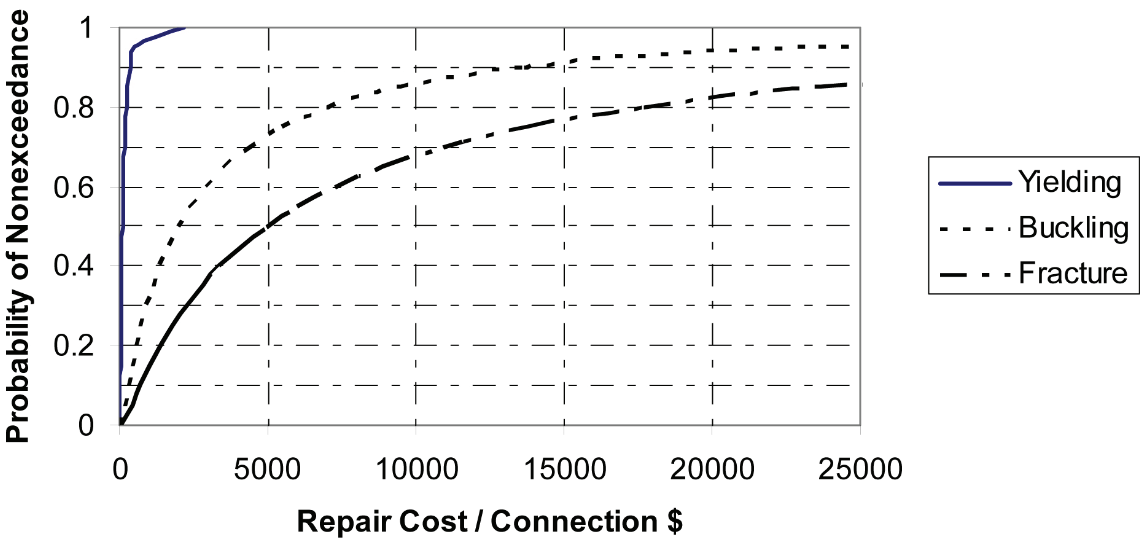


Figure A-13 Hypothetical loss curve for repair cost of damaged beam-column connections.

The data in Figure A-13 are based on the estimated cost of repairing moment-resisting steel frames developed during the FEMA/SAC program.

Figure A-14 is a hypothetical loss curve for fatalities in an office building, given that a story collapse occurs. It shows a 20% chance of 0.2 or fewer fatalities per 1,000 square feet of floor area in the story, a 50% chance of 0.5 or fewer fatalities per 1,000 square feet of floor area and roughly an 80% chance of one or fewer fatalities per 1,000 square feet of floor area. This variability may be attributed to the fact that the number of people present in a building varies with the time of day and day of the week and also that collapse of a story can be either partial or total. Obviously, loss curves of this type are highly dependent on the type of building occupancy.

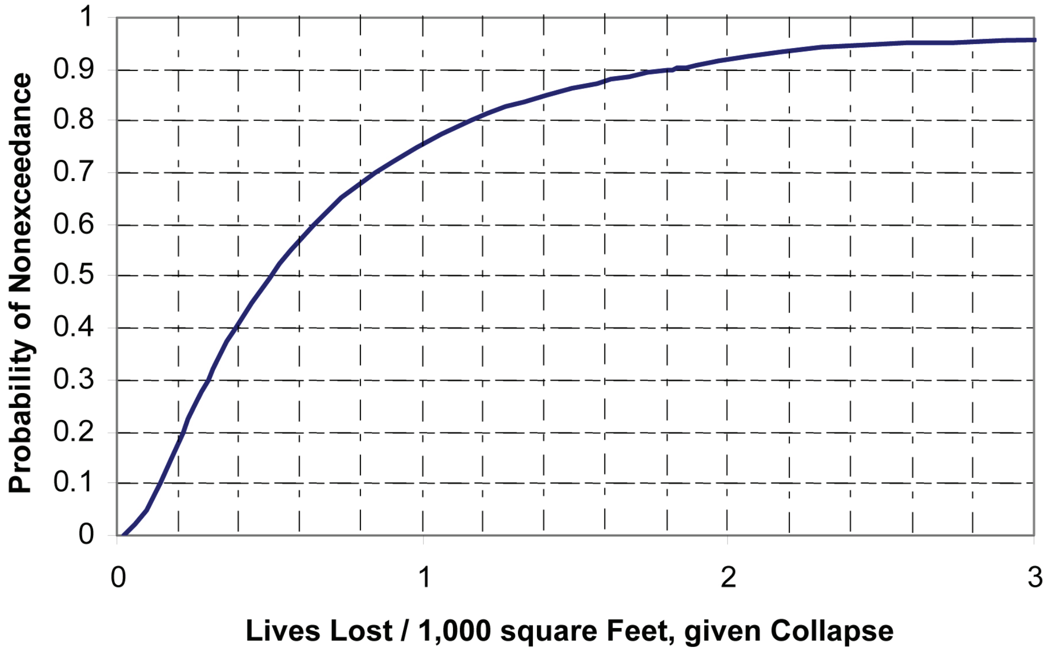


Figure A-14 Hypothetical loss curve for fatalities, given collapse.

Loss curves (not shown here) for various nonstructural components and systems could be developed in a manner similar to those indicated in Figures A-13 and A-14.

A.9 Predicting Loss as a Function of Damage

Given the hazard functions for appropriate intensity measures, response curves for the structure and flexible nonstructural components, fragility curves for the structure and its nonstructural components, and loss curves for each of these, it becomes possible to characterize building performance, and thereby, building performance objectives, in a number of different ways.

Many stakeholders will wish to deal with performance and risk information on a scenario basis. For example, they may wish to know how much loss they can expect, given that a certain magnitude earthquake occurs. Within this group of stakeholders/decision-makers, some may wish to know this information on an upper bound or "probable maximum" basis, while others will want to know a "best estimate" of the probable losses, given the scenario. Still others may wish to know the probability in a single year or number of years that losses of a given size will be experienced. Each of these, and other means of expressing loss, can be derived with the use of the hazard, response, fragility, and loss functions. Appendices B and C present an example application illustrating two different potential methods of illustrating these procedures to derive such performance assessments.

Appendix B

Example Application of Seismic Performance Assessment Using Numerical Integration Techniques

This Appendix illustrates the application of the performance assessment process described in Appendix A. This application estimates potential future losses for a scenario earthquake for a hypothetical building. Note that for this simple illustrative example, nonstructural fragilities and losses are neglected. However, in practice, they could be and should be treated in an identical manner as the structural fragilities and losses illustrated here. In this illustrative example, a process of numerical integration is used to calculate expected losses as the probability of response (engineering demand parameter) given a level of shaking intensity (intensity measure), the probability of damage given response and the probability of loss given damage, summed over all possible intensity levels, considering the probability of each intensity level. If the various intensity, response, damage and loss functions are represented as mathematical expressions, such as lognormal distributions with defined median value and variance, it is possible to derive a closed-form solution for these various integrations that can the be used to calculate probable losses directly. Appendix C presents an example illustration of the closed-form approach to solution.

It is also possible, although not illustrated by example in this report, to calculate the probable performance of a building using Monte Carlo solution techniques. In this approach, a large number of simulations are performed, varying assumptions as to ground motion, structural properties, damage, and loss, consistent with the hazard, response, fragility and loss function probabilities previously discussed and calculating expected loss in each case. This results in a statistical distribution for the expected loss at varying intensity levels. The advantage of the Monte Carlo solution technique is that it permits a confidence level, other than the mean, to be directly associated with the performance assessment. It does, however, require a large number of computations. Any of these approaches, or perhaps combinations of these approaches, can be incorporated into the next generation performance-based assessment and design guidelines.

In this example, the mean scenario repair cost is calculated for a moment-resisting steel frame building, for a scenario event having a 10% chance of exceedance in 50 years, or an annual probability of exceedance of 0.0021. The building is a three-story structure with a floor plate that is 140 foot long on each side, having bays that are 28 feet square and three, contiguous moment-resisting frames on each side of the structure. Thus, there are 19,600 square feet per floor level, 58,800 square feet total in the building and 108 individual beam-column connections in the structure. For the purposes of this example, it has been assumed that the response is identical in each direction and in each of the three stories and thus the probability of being damaged to the various states is the same for each story and in each principal direction of the building.

Figure B-1, is the hazard curve for the site of the hypothetical building. It indicates the annual probability of exceeding various levels of ground shaking intensity, expressed in terms of peak ground acceleration. Three curves are shown on the figure representing median values, values with a 10% confidence level (i.e., 90% chance of being exceeded) and values with a 90% confidence level (i.e. 10% chance of being exceeded), reflecting the aleatory uncertainty (randomness) associated with prediction of the probability of experiencing ground motion of different intensities. This figure expresses ground shaking intensity in terms of peak ground acceleration however other intensity measures, such as first mode elastic spectral response acceleration could also have been used.

In Figure B-1, a horizontal line is drawn across the hazard curve at an annual probability of exceedance of 0.0021, representing the scenario event. Where this horizontal line intersects the 10% confidence level curve, one can read that there is less than a 10% chance that the peak ground acceleration resulting from an event with a 10% chance of exceedance in 50 years would be less than 0.22g. At the median curve, one can read that there is a 50% chance that the ground motion resulting from an event with a 10% chance of exceedance in 50 years would produce a peak ground acceleration of 0.42g or less. At the 90% confidence level, one can read that there is a 90% chance that the scenario event with a 10% chance of exceedance in 50 years would produce ground motion with a peak ground acceleration less than or equal to 0.80g. By interpolation, it is possible to estimate the peak ground acceleration associated with any confidence level for this 10%-50 year scenario event. Table B-1 is such a tabulation of these peak ground accelerations at confidence intervals of 5%.

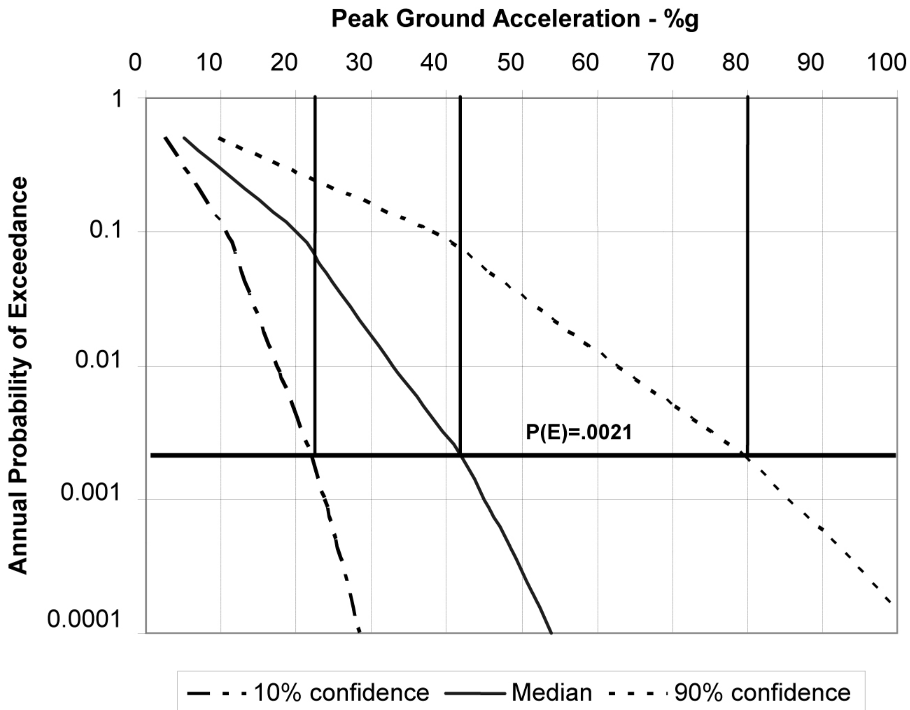


Figure B-1 Hazard Curve with intensity at 10% chance of exceedance in 50 years indicated

Table B-1 Peak Ground Acceleration for 10%/50 Year Event, at Various Confidence Levels

Confidence Level[1]	pga - g	Confidence Level[1]	pga – g	Confidence Level[1]	pga – g
5%	0.18	40%	0.37	75%	0.59
10%	0.22	45%	0.40	80%	0.65
15%	0.25	50%	0.42	85%	0.71
20%	0.28	55%	0.45	90%	0.80
25%	0.30	60%	0.48	95%	0.96
30%	0.33	65%	0.51		
35%	0.35	70%	0.55		

[1]Confidence level is an expression of uncertainty with regard to the true value of a random variable. The confidence level represents the probability that the true value is less than or equal to the stated value.

Figure B-2 is a response curve for the hypothetical structure, indicating the probability of experiencing various levels of interstory drift as a function of the peak ground acceleration experienced by the structure. This response curve is derived by performing structural analyses for a number of ground motions and ground motion intensity levels, as described in Appendix A.

Entering Figure B-2 at a specific peak ground acceleration it is possible to determine the likelihood of experiencing a given level of interstory drift. For example, at a peak ground acceleration of 0.8g, there is a 10% confidence that interstory drift will be 3.5 inches or less, a 50% confidence that it will be less than or equal to 4.8 inches and a 90% confidence that it will not exceed 6.7 inches.

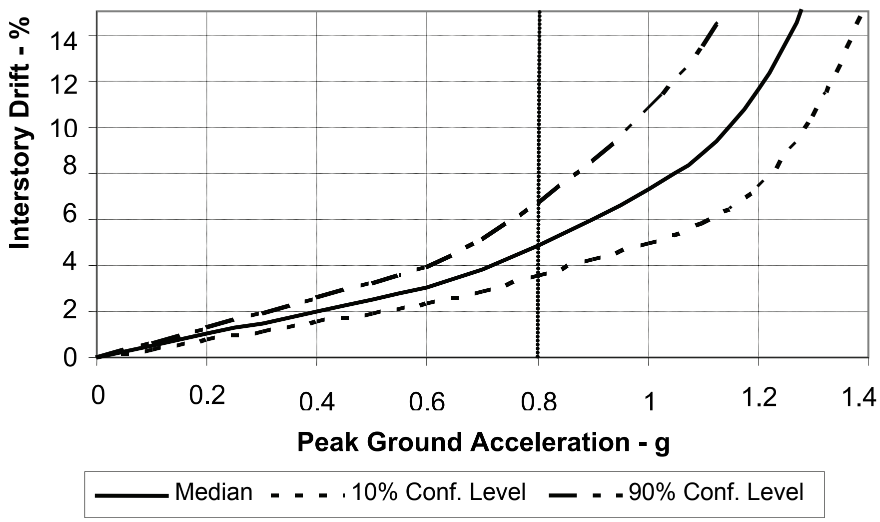


Figure B-2 Response curve for hypothetical structure

Table B-1 described above shows at varying levels of confidence, the level of peak ground acceleration expected for the scenario event being analyzed. Table B-2 presents this same data in a somewhat different format. In Table B-2 a series of confidence bands, each 10% wide are defined. For each 10% confidence band, a central value of the confidence and the central value of the pga is indicated. In order to perform the integration to determine probable loss, it can be said that each of the pga values indicated in the third column of Table B-2 has a 10% chance of occurrence, given that the scenario earthquake event occurs.

For each of the pga values indicated in Table B-2, it is possible to enter Figure B-2 and determine the probability that the hypothetical structure will be excited to various levels of peak interstory drift. This exercise has been done, and is shown in Table B-3, which indicates the distribution of drift response for ground shaking having a 10% chance of exceedance in 50 years, considering uncertainty in both intensity and structural response.

Table B-2 Central Value of PGA for Scenario Event within Confidence Bands

Confidence Range	Mid Range Value of Confidence	Mid Range Value of PGA - g
0-10%	5%	0.18
10%-20%	15%	0.258
20%-30%	25%	0.30
30%-40%	35%	0.35
40%-50%	45%	0.40
50%-60%	55%	0.45
60%-70%	65%	0.51
70%-80%	75%	0.59
80%-90%	85%	0.71
90%-100%	95%	0.96

Table B-3 Distribution of Interstory Drift for the 10%/50 – Year Event

Col 1	Col 2	Col 3	Col 4	Col 5	Col 6	Col 7	Col 8	Col 9	Col 10	Col 11	Col 12	Col 13
Confidence Interval for pga	*Median pga g*	*Median drift - in*	*Drift Demand at Indicated Confidence Level in Hazard and Response*									
			0-10%	*10-20%*	*20-30%*	*30-40%*	*40-50%*	*50-60%*	*60-70%*	*70-80%*	*80-90%*	*90-100%*
0%-10%	0.19	0.93	0.64	0.73	0.80	0.85	0.90	0.96	1.02	1.09	1.18	1.36
10%-20%	0.25	1.26	0.86	0.99	1.08	1.15	1.23	1.30	1.38	1.47	1.60	1.84
20%-30%	0.30	1.51	1.04	1.19	1.29	1.38	1.47	1.56	1.65	1.77	1.92	2.21
30%-40%	0.35	1.75	1.20	1.38	1.50	1.60	1.70	1.80	1.91	2.04	2.22	2.55
40%-50%	0.40	1.99	1.36	1.57	1.70	1.82	1.93	2.05	2.17	2.32	2.53	2.90
50%-60%	0.45	2.26	1.55	1.78	1.93	2.06	2.19	2.32	2.47	2.63	2.86	3.29
60%-70%	0.51	2.57	1.76	2.02	2.20	2.35	2.50	2.64	2.81	3.00	3.26	3.75
70%-80%	0.59	2.97	2.03	2.34	2.54	2.72	2.88	3.06	3.24	3.47	3.77	4.33
80%-90%	0.71	3.91	2.68	3.08	3.35	3.58	3.80	4.03	4.28	4.57	4.97	5.71
90%-100%	0.96	6.79	4.65	5.35	5.81	6.21	6.59	6.99	7.42	7.93	8.62	9.91

Each row in Table B-3 represents a 10% confidence interval with regard to evaluation of intensity (peak ground acceleration). Columns 1 and 3 are identical to the entries in Table B-2, Columns 1 and 2. Column 3 of Table B-3 tabulates the median estimate of drift response, from the response functions illustrated in Figure B-2, evaluated at each of the mid-range ground motion intensities indicated in column 2. Columns 4 through 13 indicate the mid-range values of the interstory drift response evaluated for 10 different response confidence intervals. These are calculated using the median values of column 3 and coefficients of variation obtained from structural analyses of the hypothetical structure, assuming a lognormal distribution for drift response. Since there are 10 confidence intervals with regard to evaluation of intensity (rows) and 10 confidence intervals with regard to evaluation of response (columns) each entry in columns 4 through 13 has a 1% chance of occurrence, given that the scenario 10%/50-year ground shaking event is experienced.

The data contained in columns 4 through 13 of Table B-3 can be presented more simply by doing a frequency analysis of the data and representing it in the form of a cumulative distribution function that indicates the conditional probability of nonexceedance of drift responses at different levels, given the occurrence of the scenario 10%- 50 year ground shaking event. Figure B-3 presents this distribution.

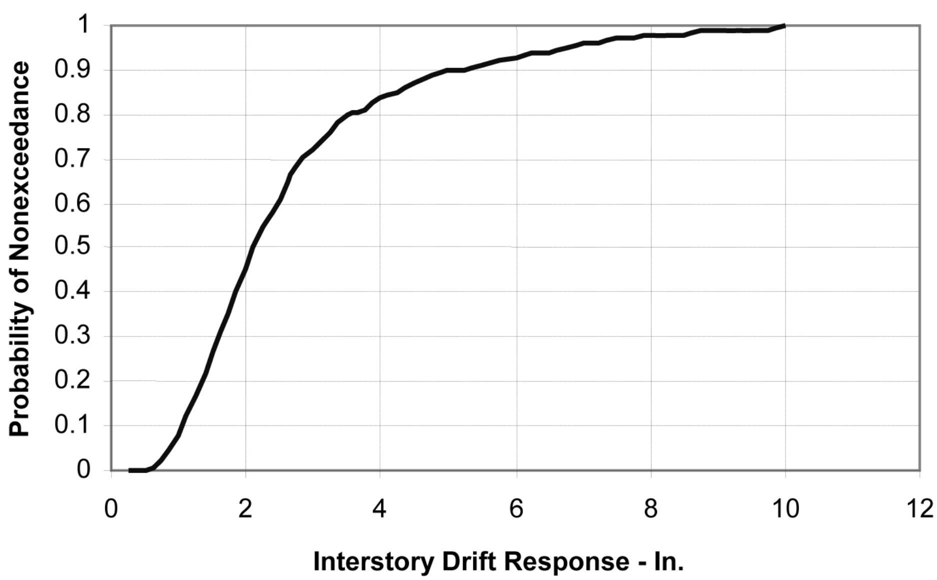


Figure B-3 Cumulative probability distribution for interstory drift response, conditioned on the 10%/50 year scenario event.

Entering Figure B-3 one can read that if a 10%-50 year earthquake shaking event occurs, there is a 45% chance that the hypothetical buildings would experience a peak interstory drift of 2 inches or less. Conversely, one can read that there is a 55% chance that the drift experienced in such an event will be larger than 2 inches. Values of interstory drift at other probabilities of exceedance or nonexceedance can be similarly evaluated from the figure.

The next step on the process is to calculate the probability of being in each of several damage states, given the structural response distribution shown in Figure B-3. Three local damage states (beam flange yielding, beam flange buckling and beam flange fracture) are considered. For this purpose, the same fragility data, previously presented in Figure A-10 is used. Since, for this example, structural response is parameterized by interstory drift in inches, the data in Figure A-10 has been converted to these units, by assuming that a typical story has a height of 12 feet (144 inches). Figure B-4 presents this converted fragility data.

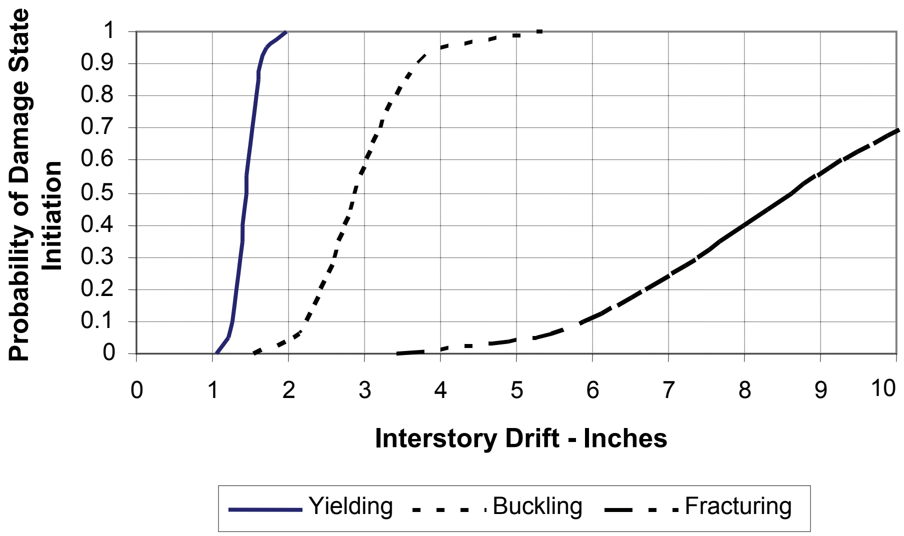


Figure B-4 Fragilities for local damage to steel moment frame connection assemblies

Four global damage states (1% permanent drift, 2% permanent drift, 3% permanent drift and collapse) are also considered. Fragilities for these damage states were previously presented in Figure A-11. Figure B-5, presents this same data with the units of interstory drift converted from percent of story height to inches. As with the local fragilities, a story height of 144 inches has been assumed.

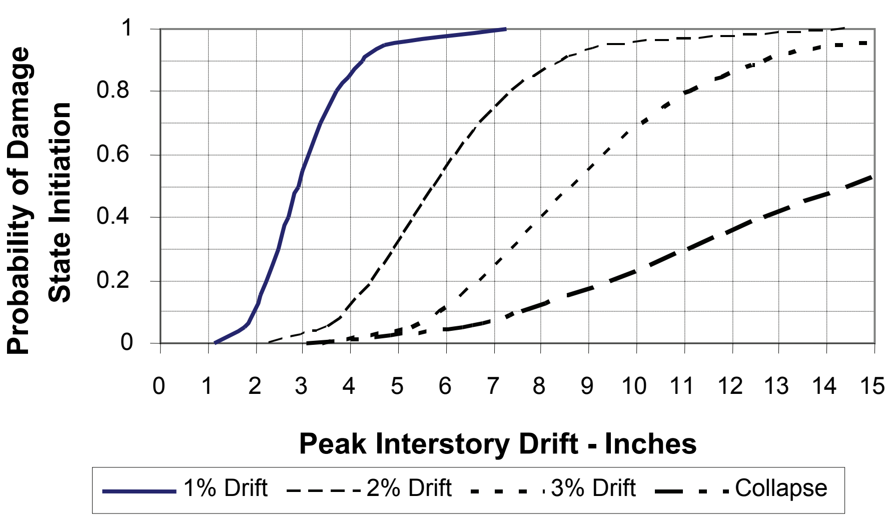


Figure B-5 Fragilities for global damage to steel moment frame building

Table B-4 Calculation of Probability of Each Local Damage State

	Col 2	Col 3	Col 4	Col 5	Col 6	Col 7	Col 8	Col 9
Interstory Drift Response Range (in.)	*Mid Value Interstory Drift (in.)*	*Probability of Occurrence*	*Conditional Probability of Yielding*	*Incremental Probability of Yielding*	*Conditional Probability of Buckling*	*Incremental Probability of Buckling*	*Conditional Probability of Fracturing*	*Incremental Probability of Fracturing*
0-.5	0.25	0	0	0	0	0	0	0
.5-1	0.75	0.08	0	0	0	0	0	0
1-1.5	1.25	0.19	0.08	0.01	0	0	0	0
1.5-2	1.75	0.18	0.97	0.18	0.01	0.001	0	0
2-2.5	2.25	0.16	1.00	0.16	0.11	0.017	0	0
2.5-3	2.75	0.11	1.00	0.11	0.41	0.045	0	0
3-3.5	3.25	0.08	1.00	0.08	0.73	0.058	0.001	0.0001
3.5-4	3.75	0.04	1.00	0.04	0.91	0.036	0.003	0.0001
4-4.5	4.25	0.03	1.00	0.03	0.97	0.029	0.009	0.0003
4.5-5	4.75	0.03	1.00	0.03	0.99	0.030	0.023	0.0007
5-5.5	5.25	0.01	1.00	0.01	1.00	0.010	0.048	0.0005
5.5-6	5.75	0.02	1.00	0.02	1.00	0.020	0.087	0.0017
6-6.5	6.25	0.01	1.00	0.01	1.00	0.010	0.140	0.0014
6.5-7	6.75	0.02	1.00	0.02	1.00	0.020	0.205	0.0041
7-7.5	7.25	0.01	1.00	0.01	1.00	0.010	0.279	0.0028
7.5-8	7.75	0.01	1.00	0.01	1.00	0.010	0.359	0.0036
8-8.5	8.25	0.005	1.00	0.005	1.00	0.005	0.439	0.0026
8.5-9	8.75	0.005	1.00	0.005	1	0.005	0.517	0.0026
9-9.5	9.25	0.005	1.00	0.005	1	0.005	0.590	0.0033
9.5-10	9.75	0.005	1.00	0.005	1	0.006	0.656	0.0033
Total Probability of Damage State Initiation				0.740		0.317		0.027
Total Probability of Damage State Occurrence				**42.3%**		**29.0%**		**2.70%**

For a given damage state (e.g., beam flange buckling) the probability of being damaged to this damage state is evaluated as the conditional probability of the damage state (beam flange buckling) given a level of response times the probability of the response occurring, integrated over all possible levels of response. Table B-4 illustrates this calculation of the probability of each of the three local damage states, i.e., yielding, buckling and fracture.

In Table B-4, the first column indicates the increments of response drift, over which the integration is being performed. The second column is the mid-range value for each increment. The third range is the probability of occurrence of drift response within the increment. This is calculated as the difference of the probability of nonexceedance of the interstory drift at the upper end of the increment, obtained from Figure B-3, and the probability of nonexceedance at the lower end of the increment, also obtained from Figure B-3. Columns 4 and 5 are the integration for the "yielding" state, columns 6 and 7 for the "buckling" state, and columns 8 and 9 for the "fracturing" state. For each of these states, the first of the two columns represents the conditional probability that damage of the level indicated by this state or a more severe state will occur, given the drift response of the amount represented in column 2. This is evaluated from the data presented in Figure B-4. The second of the two columns is the incremental contribution to the total probability that any given connection in the structure will be damaged to the given state (or more severe state), calculated as the product of the conditional probability that the damage state will occur at the response level (e.g., column 4 for yielding) and the probability that the response level itself will be experienced (column 3). At the bottom of each of the columns, the total probability that any connection in the structure will be damaged to the given or more severe damage level is calculated as the sum of the incremental contributions in the column above. The last row shows the total probability that any connection in the structure will be damaged to the given level if the scenario 10%/50 year event is experienced, calculated as the difference between the total probability that the connection is damaged to a given or more severe level and the total probability that it is damaged to the next higher level. Thus, for this example, given the scenario event, there is a 42% chance that any particular beam-column joint in the structure will initiate yielding but not buckling, a 29% chance that it will initiate beam flange buckling, but not fracturing and a 3% chance that it will initiate beam flange fracture. The chance that there would be no damage at all to any particular joint is estimated as 100% minus the sum of the probabilities for each of these damage states, or 26%.

Table B-5 illustrates a similar calculation for the global damage states, of varying levels of permanent interstory drift and collapse. In this table, damage states consisting of 1%, 2%, and 3% permanent interstory drift and story collapse are shown. The conditional probability of each of these states initiating, as a function of response, are taken from the data shown in Figure B-5. Total probabilities of each of these damage states, given the scenario event is calculated, as described above for the local damage states. Total probabilities calculated are 24% for 1% permanent drift, 6% for 2% permanent drift, 2% for 3% permanent drift and 1% for collapse. The probability of no significant global damage is calculated as 100% minus the sum of the probabilities for each of these states, or 67%.

Table B-5 Calculation of Probability of Each Global Damage State, Given the 10% - 50 Year Event

Col 1	Col 2	Col 3	Col 4	Col 5	Col 6	Col 7	Col 8	Col 9	Col 10	Col 11
Response Range (in)	*Mid Value (in)*	*Probability of Occurrence*	*Conditional Probability of 1% Perm. Drift*	*Incremental Probability of 1% Perm. Drift*	*Conditional Probability of 2% Perm. Drift*	*Incremental Probability of 2% Perm. Drift*	*Conditional Probability of 3% Perm. Drift*	*Incremental Probability of 3% Perm. Drift*	*Conditional Probability of Collapse*	*Incremental Probability of Collapse*
0-.5	0.25	0	0	0	0	0	0	0	0	0
.5-1	0.75	0.08	0	0	0	0	0	0	0	0
1-1.5	1.25	0.19	0	0	0	0	0	0	0	0
1.5-2	1.75	0.18	0.05	0.009	0	0	0	0	0	0
2-2.5	2.25	0.16	0.21	0.033	0	0	0	0	0	0
2.5-3	2.75	0.11	0.44	0.048	0.01	0	0	0	0	0
3-3.5	3.25	0.08	0.66	0.052	0.03	0.002	0.001	0	0.001	0
3.5-4	3.75	0.04	0.81	0.032	0.08	0.003	0.003	0	0.004	0
4-4.5	4.25	0.03	0.91	0.027	0.16	0.005	0.01	0	0.007	0
4.5-5	4.75	0.03	0.95	0.029	0.26	0.008	0.02	0.001	0.013	0
5-5.5	5.25	0.01	0.98	0.010	0.38	0.004	0.05	0.000	0.022	0
5.5-6	5.75	0.02	0.99	0.020	0.50	0.010	0.09	0.002	0.033	0.001
6-6.5	6.25	0.01	1.00	0.010	0.61	0.006	0.14	0.001	0.048	0.001
6.5-7	6.75	0.02	1.00	0.020	0.70	0.014	0.21	0.004	0.065	0.001
7-7.5	7.25	0.01	1.00	0.010	0.78	0.008	0.28	0.003	0.085	0.001
7.5-8	7.75	0.01	1.00	0.010	0.84	0.008	0.36	0.004	0.108	0.001
8-8.5	8.25	0.005	1.00	0.005	0.88	0.004	0.44	0.002	0.133	0.001
8.5-9	8.75	0.005	1.00	0.005	0.92	0.005	0.52	0.003	0.159	0.001
9-9.5	9.25	0.005	1.00	0.005	0.94	0.005	0.59	0.003	0.188	0.001
9.5-10	9.75	0.005	1.00	0.005	0.96	0.005	0.66	0.003	0.218	0.001
Total Probability of Damage State Initiation				0.330		0.088		0.027		0.009
Total Probability of Damage State Occurrence				**24.2%**		**6.1%**		**1.8%**		**0.9%**

Next, it is necessary to know the probable losses, given that a damage state is experienced. Figure B-6 indicates the probability of incurring various levels of repair cost for a damaged connection assembly, as a function of the damage state experienced. This same data was previously presented as Figure A-13.

Table B-6 illustrates the calculation of probable repair cost per beam-column connection, for each of the three connection damage states: yielding, flange buckling and flange fracturing. This is accomplished by integrating over all possible individual connection repair costs, the probability that this repair cost would be experienced, given that the connection is damaged to the specified state. In Table B-6, the first two columns indicate the upper and lower bounds for the incremental repair costs over which the integration is performed. The third column gives the mid-range cost for the given

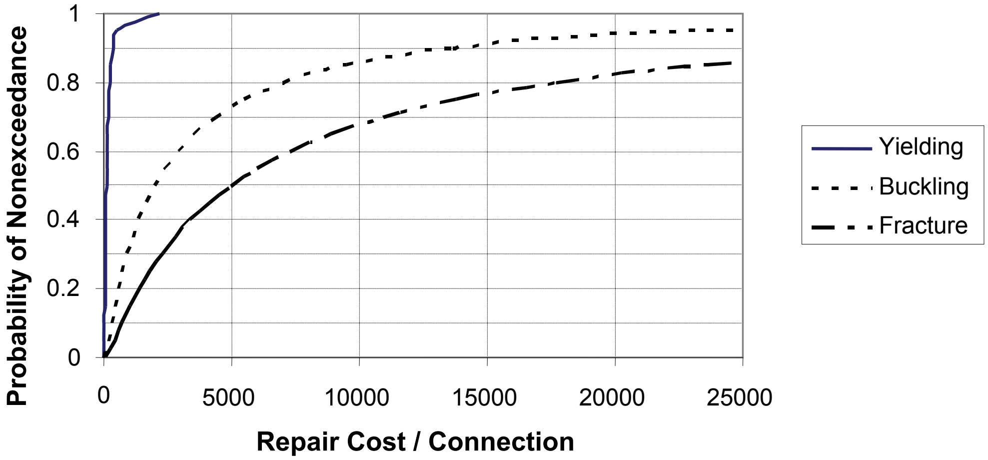


Figure B-6 Probability of Experiencing Various Repair Costs as Function of Connection Assembly Damage State

Table B-6 Calculation of Probable Repair Cost, Given that a Connection Damage State is Experienced

Col 1	Col 2	Col 3	Col 4	Col 5	Col 6	Col 7	Col 8	Col 9	Col 10	Col 11	Col 12
Repair Cost/Connection			*Yielding*			*Buckling*			*Fracturing*		
Low	High	Mid-pt	Prob. of NonExc.	Prob. Of Occurrence	Incremental Probable Loss	Prob. of NonExc.	Prob. of Occurrence	Incremental Probable Loss	Prob. of NonExc.	Prob. of Occurrence	Incremental Probable Loss
$-	$75	$38	0.3868	0.3868	$14.50	0.0143	0.0143	$0.54	0.0026	0.0026	$0.10
$75	$125	$100	0.5883	0.5883	$58.83	0.0323	0.0323	$3.23	0.0070	0.0070	$0.70
$125	$250	$188	0.8202	0.2320	$43.49	0.0828	0.0506	$9.48	0.0229	0.0159	$2.99
$250	$500	$375	0.9462	0.1260	$47.25	0.1777	0.0949	$35.57	0.0624	0.0395	$14.81
$500	$750	$625	0.9780	0.0318	$19.88	0.2566	0.0789	$49.31	0.1030	0.0406	$25.37
$750	$1,000	$875	0.9893	0.0113	$9.89	0.3220	0.0654	$57.24	0.1416	0.0387	$33.83
$1,750	$2,000	$1,875	0.9986	0.0093	$17.40	0.5000	0.1780	$333.74	0.2706	0.1290	$241.88
$2,750	$3,000	$2,875	0.9997	0.0010	$2.97	0.6065	0.1065	$306.30	0.3667	0.0961	$276.22
$3,750	$4,000	$3,875	0.9999	0.0002	$0.86	0.6780	0.0715	$276.89	0.4409	0.0741	$287.33
$4,750	$5,000	$4,875	1.0000	0.0001	$0.33	0.7294	0.0514	$250.38	0.5000	0.0591	$288.26
$5,750	$6,000	$5,875	1.0000	0.0000	$0.14	0.7680	0.0387	$227.28	0.5484	0.0484	$284.18
$6,750	$7,000	$6,875	1.0000	0.0000	$0.07	0.7982	0.0302	$207.28	0.5887	0.0404	$277.56
$7,750	$8,000	$7,875	1.0000	0.0000	$0.04	0.8223	0.0241	$189.92	0.6230	0.0342	$269.67
$8.750	$9,000	$8,875	1.0000	0.0000	$0.02	0.8420	0.0197	$174.78	0.6524	0.0294	$261.20
$9,750	$10,000	$9,875	1.0000	0.0000	$0.01	0.8584	0.0164	$161.49	0.6780	0.0256	$252.57
$10,000	$15,000	$12,500	1.0000	0.0000	$0.02	0.9104	0.0521	$650.65	0.7680	0.0900	$1,125.57
$15,000	$20,000	$17,500	1.0000	0.0000	$0.00	0.9376	0.0272	$476.13	0.8223	0.0543	$949.68
$20,000	$25,000	$22,500	1.0000	0.0000	$0.00	0.9539	0.0163	$366.23	0.8584	0.0360	$811.06
$850,000	$900,000	$875,000	1.0000	0.0000	$0	1.0000	0.0000	$3.60	0.9997	0.0000	$35.50
$900,000	$950,000	$925,000	1.0000	0.0000	$0	1.0000	0.0000	$3.09	0.9998	0.0000	$31.22
$950,000	**$1,000,000**	**$975,000**	1.0000	0.0000	$0	1.0000	0.0000	$2.68	0.9998	0.0000	$27.61
					$215.73			**$6,397.12**			**$15,370.52**

increment. Columns 4, 7 and 10 indicate the probability of experiencing damage less severe than the high end of each incremental range for the yield, buckling and fracturing states, respectively. Columns 5, 8 and 11 indicate the probability of damage costing within each range, calculated as the difference between the probability of damage less severe than the high end of that range and the high end of the next lower range. Columns 6, 9 and 12 indicate the incremental contribution to the total probable repair cost from the various ranges, calculated as the mid-range repair cost for each range factored by the probability of the cost being within the range. The total expected cost of repairing damage for the category is calculated as the sum of the incremental costs for each of the ranges and is approximately $215 per yielded connection, $6,400 per buckled connection and $15,000 per fractured connection.

Table B-7 performs a similar integration to determine the probable costs associated with repair of global damage in the building, if the building is damaged to each of the global damage states: 1% permanent drift, 2% permanent drift, 3% permanent drift and collapse, respectively. For the purposes of this calculation it has arbitrarily been assumed that the median cost for repair of damage for each of these states is respectively $37.50 per square foot, $47 per square foot, $56 per square foot and $200 per square foot, respectively. Coefficients of variation for these repair costs have respectively been assumed as 40% for 1% drift, 50% for 2% and 3% drift and 30% for the collapse state. The probable cost of repair for these states is respectively found to be $46/sq foot of story space for 1% permanent drift, $53/sq foot of story space for 2% story drift, $64/square foot of story space for 3% story drift and $210/square foot of building space for the collapse state.

It should be noted that in this example, it has been assumed that the probability of experiencing given levels of local damage is uncoupled from the probability of experiencing particular levels of global damage and that the cost associated with repair of global damage and that related to repair of local damage are also uncoupled. In actuality, neither of these assumptions is correct and rather than using independent probabilities for these damage states, joint probability distributions should be used. Development of effective and practical methods of accounting for these joint probabilities is needed and will be conducted as part of the Phase 1 FEMA 445 program.

Table B-7 Calculation of Probable Repair Costs for Global Damage

Repair Cost/Square Feet			1% Permanent Drift			2% Permanent Drift			3% Permanent Drift			Collapse		
Low	*High*	*Mid-Range*	*Prob. of NonExc.*	*Prob. of Occurrence*	*Incremental Probable Loss*	*Prob. of NonExc.*	*Prob. of Occurrence*	*Incremental Probable Loss*	*Prob. of NonExc.*	*Prob. of Occurrence*	*Incremental Probable Loss*	*Prob. of NonExc.*	*Prob. of Occurrence*	*Incremental Probable Loss*
$0	$10	$5	0.000	0.000	$0.00	0.001	0.001	$0.01	0.000	0.000	$0.00	0.000	0.000	$0.00
$10	$20	$15	0.058	0.058	$0.86	0.044	0.043	$0.65	0.019	0.019	$0.29	0.000	0.000	$0.00
$20	$30	$25	0.288	0.230	$5.76	0.186	0.142	$3.55	0.104	0.085	$2.13	0.000	0.000	$0.00
$30	$40	$35	0.564	0.276	$9.65	0.376	0.189	$6.63	0.248	0.143	$5.02	0.000	0.000	$0.00
$40	$50	$45	0.764	0.200	$9.00	0.551	0.176	$7.91	0.407	0.159	$7.16	0.000	0.000	$0.00
$50	$60	$55	0.880	0.116	$6.38	0.689	0.138	$7.58	0.551	0.144	$7.95	0.000	0.000	$0.00
$60	$70	$65	0.941	0.061	$3.94	0.789	0.099	$6.47	0.669	0.118	$7.65	0.000	0.000	$0.01
$70	$80	$75	0.971	0.030	$2.27	0.857	0.069	$5.16	0.759	0.090	$6.78	0.001	0.001	$0.07
$80	$90	$85	0.986	0.015	$1.26	0.904	0.047	$3.95	0.826	0.067	$5.69	0.004	0.003	$0.23
$90	$100	$95	0.993	0.007	$0.68	0.935	0.031	$2.96	0.875	0.049	$4.63	0.010	0.007	$0.62
$100	$120	$110	0.998	0.005	$0.58	0.970	0.035	$3.83	0.935	0.060	$6.61	0.044	0.034	$3.73
$120	$130	$125	0.999	0.001	$0.11	0.979	0.009	$1.17	0.953	0.018	$2.24	0.076	0.031	$3.90
$130	$140	$135	1.000	0.000	$0.06	0.986	0.006	$0.86	0.966	0.013	$1.73	0.117	0.042	$5.63
$140	$150	$145	1.000	0.000	$0.03	0.990	0.004	$0.63	0.975	0.009	$1.33	0.169	0.052	$7.48
$150	$160	$155	1.000	0.000	$0.02	0.993	0.003	$0.46	0.982	0.007	$1.03	0.228	0.060	$9.25
$160	$170	$165	1.000	0.000	$0.01	0.995	0.002	$0.34	0.987	0.005	$0.79	0.294	0.066	$10.81
$170	$180	$175	1.000	0.000	$0.01	0.996	0.001	$0.25	0.990	0.003	$0.61	0.363	0.069	$12.03
$180	$190	$185	1.000	0.000	$0.00	0.997	0.001	$0.19	0.993	0.003	$0.47	0.432	0.069	$12.84
$190	$200	$195	1.000	0.000	$0.00	0.998	0.001	$0.14	0.994	0.002	$0.36	0.500	0.068	$13.24
$200	$250	$225	1.000	0.000	$0.00	1.000	0.001	$0.33	0.999	0.004	$0.94	0.772	0.272	$61.09
$250	$300	$275	1.000	0.000	$0.00	1.000	0.000	$0.08	1.000	0.001	$0.28	0.912	0.140	$38.56
$300	$350	$325	1.000	0.000	$0.00	1.000	0.000	$0.02	1.000	0.000	$0.09	0.969	0.057	$18.59
$350	$400	$375	1.000	0.000	$0.00	1.000	0.000	$0.01	1.000	0.000	$0.03	0.990	0.021	$7.74
$400	$450	$425	1.000	0.000	$0.00	1.000	0.000	$0.00	1.000	0.000	$0.01	0.997	0.007	$2.97
$450	$500	$475	1.000	0.000	$0.00	1.000	0.000	$0.00	1.000	0.000	$0.00	0.999	0.002	$1.10
$500	$550	$525	1.000	0.000	$0.00	1.000	0.000	$0.00	1.000	0.000	$0.00	1.000	0.001	$0.40
$550	$600	$575	1.000	0.000	$0.00	1.000	0.000	$0.00	1.000	0.000	$0.00	1.000	0.000	$0.14
					$40.63			**$53.16**			**$63.82**			**$210.42**

The final step is to compute the expected losses, given that the scenario event is experienced. This is performed by summing over all damage states, the probability that the damage state is experienced and the probable (expected) loss given that the state is experienced. Table B-8 illustrates this calculation. Total expected cost to repair the structure following the scenario event is found to be approximately $1,800,000, or approximately $31/ sq ft.

Table B-8 Calculation of Expected Repair Cost, Given 10%/50-Year Event

Col 1	Col 2	Col 3	Col 4	Col 5	Col 6
Damage State Yielding Buckling Fracture	*Probability of Occurrence*	*Probable Cost per Connection*	*Expected Cost per Connection*	*Expected Global Cost*	*Total Expected Cost*
1% drift	0.423	$215.73	$91.25	n/a	$9,855.22
2% drift	0.290	$6,397.12	$1,855.16	n/a	$200,357.81
3% drift	0.027	$15,370.52	$415.00	n/a	$44,820.43
Collapse	0.243	n/a	n/a	$592,400.31	$592,400.31
	0.061	n/a	n/a	$194,571.90	$194,571.90
	0.018	n/a	n/a	$689,246.69	$689,246.69
	0.009	n/a	n/a	$113,629.31	$113,629.31
				Aggregate of all damage states:	**$1,844,881.67**

The actual losses in any actual occurrence of the 10%-50 year event could vary substantially from these expected values depending on the actual value of the ground motion experienced at the site, given that the 10%/50 year event occurs, the actual response of the structure given this ground motion, the actual damage state that the structure experiences, the actual number of people present in the building, and the response time and efficiency of the owner, tenants and contractors in effecting repairs. Possible variability in each of these factors, including the variability in the ground motion, the variability in structural response, the variability in the damage state given the response, and the variability in the human factors, has been explicitly considered in the hazard, response, fragility and loss functions, as described above. However, the integration process results in an average or mean value of the loss, considering all this potential variability. Thus, there is a significant probability, on the order of 40%, that actual losses could be larger than this amount. Procedures for determining performance (losses) at other levels of confidence will be developed as part of the implementation of the Phase 1 FEMA 445 Program Plan.

Appendix C

Example Application of Seismic Performance Assessment Using Closed Form Solutions

This Appendix illustrates the application of a closed-form solution to the performance assessment process described in Appendix A. This example application is different from that presented in Appendix B and consists of the estimation of the annual average probability of earthquake-induced life loss for the hypothetical building. The closed-form solution is based on a procedure developed by Baker and Cornell (2003). Similar procedures have been developed to estimate other probable earthquake losses, using closed-form solutions. All of these procedures require that the hazard, response, fragility and loss functions, described in Appendix A, be represented by simple functional forms that permit closed-form integration. The representation of these various functions, in simple form, necessarily entails some approximation, which affects to some extent the prediction of performance. However, for many applications the simplification obtained by an ability to perform a closed-form solution might compensate for any loss of accuracy in the solution.

In this application, the same three-story, moment-resisting steel frame building that was the subject of evaluation using numerical integration procedures in Appendix B is used. The following assumptions and simplifications are made. The hazard function for the building site is represented in a power form as follows:

$$\lambda(x) = k_0 x^{-k} \varepsilon_{GM} \tag{C-1}$$

where $\lambda(x)$ is the annual frequency of exceedance of ground shaking equaling or exceeding intensity level x, k_0 and k are numerical coefficients chosen to fit this functional form to the site hazard curve in the range of interest, e.g., the 1/100 to 1/1000 interval, and ε_{GM} is a lognormally distributed random variable representing epistemic uncertainty related to the ground motion hazard. This form of the hazard function appears as a straight line when log $\lambda(x)$ is plotted vs log x (as shown in Figure C-1).

Epistemic is that uncertainty that occurs due a lack of knowledge on the true values of causative factors for a physical behavior. For example, epistemic uncertainty in ground motion hazard may result from a less than perfect knowledge of the mean slip rates on neighboring faults or of the depth and shear wave profiles of soils beneath a site. In Appendix A, such effects were simply termed uncertainty. Figure C-1 is a plot of the median estimate of the peak ground acceleration hazard curve for the site, previously shown in Figure A-3, plotted here in log-log coordinates. Also plotted in the figure is the explicit functional representation of the median estimate hazard curve, which has been fit to the natural curve by the function:

$$\hat{\lambda}(x) = .00001x^{-6}\varepsilon_{GM} \tag{C-2}$$

where the coefficients k_0 and k are respectively assigned values of 0.00001 and 6.

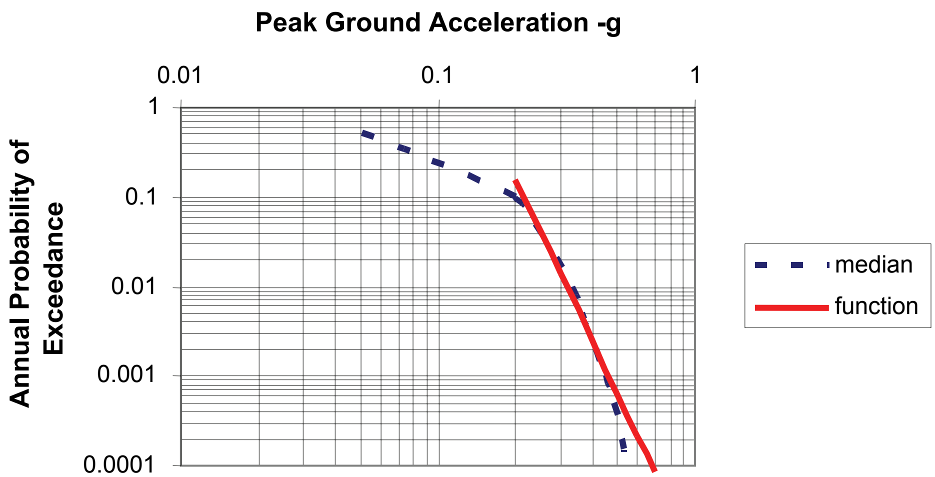


Figure C-1 Median Hazard Curve for Site

As can be seen, the functional form of the hazard curve represents the natural form of the hazard curve reasonably well for annual frequencies of exceedance ranging from 0.01 to 0.001. It diverges from the natural curve at extreme values.

Figure C-2 is the fragility data for building collapse, previously presented as one of several global damage states in Figure B-5. As can be seen, this shows a median (50% probability) value for collapse at an interstory drift of 14 inches. Figure C-3, previously shown as Figure B-2, is a response curve for the structure and indicates that the median value of peak ground acceleration at which an interstory drift of 14 inches is achieved has a value of approximately 1.25g.

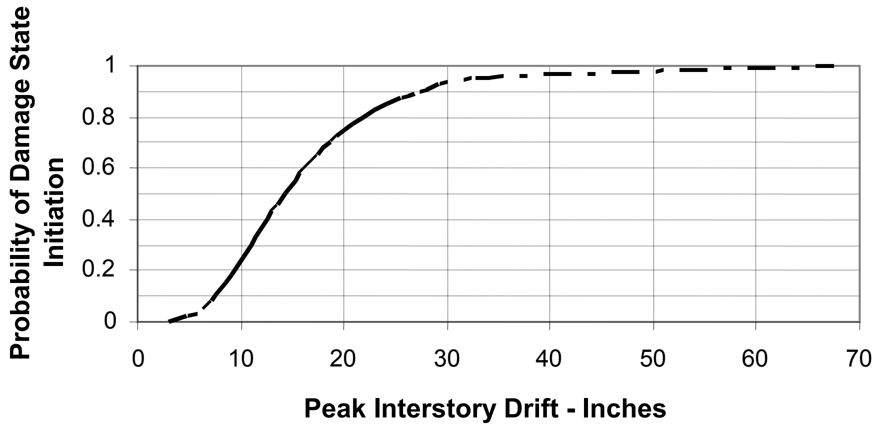


Figure C-2 Global fragility for hypothetical structure

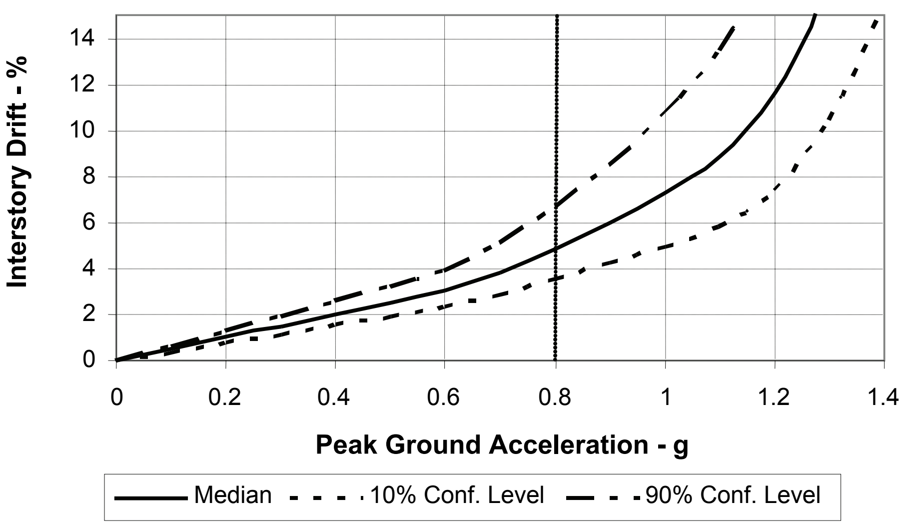


Figure C-3 Structural response curve for hypothetical building

The closed form solution for the mean estimate of the annual frequency of collapse of the structure is given by the relationship:

$$E\left|\hat{\lambda}_{collapse}\right| = k_0 \eta_c^{-k} e^{\frac{k}{2}\beta_{UT}^2} \tag{C-3}$$

where, k_0 and k are the coefficients previously described in the discussion of the hazard curve and have values of 0.0001 and 6, respectively, η_c is the median value of the ground shaking intensity at which collapse occurs, in this case 1.25g, and β_{UT} is the total dispersion considering all sources of epistemic and aleatory uncertainty and defined by the expression:

$$\beta_{UT} = \sqrt{\beta_{U,C}^2 + \beta_{R,C}^2 + \beta_{U,R}^2 + \beta_{R,R}^2 + k^2 \beta_{UGM}^2} \tag{C-4}$$

where, k is the same hazard coefficient previously described, $\beta_{U,C}$ and $\beta_{R,C}$ are respectively the epistemic and aleatory uncertainty dispersions in structure capacity, $\beta_{U,R}$ and $\beta_{R,R}$, are respectively the epistemic and aleatory uncertainty dispersions in structural response, and β_{UGM} is the epistemic uncertainty in ground motion hazard, i.e., the dispersion of the random variable defined as ε_{GM} in Eq. C-1 above. Aleatory uncertainty quantifies random, event to event, variation in behavior that can not be ascribed to quantifiable parameters, i.e., aleatory uncertainty can be characterized as random variation or randomness.

These various measures of dispersion are derived during the process of developing the hazard function, response function and damage functions, respectively, as previously described in Appendix A. For this example application, the values of these variances are as given in Table C-1.

Table C-1 Epistemic and Aleatory Uncertainty for Example Building

Quantity	Epistemic β_U	Aleatory β_R
Interstory Dift Capacity	.2	.5
Interstory Drift Response	35	.3
Ground Motion Frequency	.5	

Substituting these values into equation C-4, it is found that β_{UT} has a value of 3. Finally, substituting these values into equation C-2 is found that there is $5x10^{-5}$ annual frequency of collapse.

The annual frequency of life loss can be taken as the product of the annual frequency of collapse, times the probability of life loss given that collapse occurs. In a typical office building, during normal business hours, there is approximately one person for every 200 square feet of floor space. Earthquakes can occur at any hour of the day or night; however, buildings are occupied only about 25% of the time. Therefore, the mean average occupancy density of a building is on the order of one person per 800 square foot. Frame buildings of this type would typically collapse in a story type mechanism that involves a single story. Further, a story collapse may not be complete. If we assume that given collapse, there is a 50% chance that any person in the effected story would be a fatality and that persons on other floors would not be expected to suffer fatal injuries, we find that the mean expected number of fatalities given a collapse is the probability of collapse, calculated above as $5x10^{-5}$ per year, times the probable number of people in the affected story at the time of collapse, which is 25, times the conditional probability that each would be a fatality, given that their story collapses. This yields an expected number of fatalities per year of $6x10^{-4}$.

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