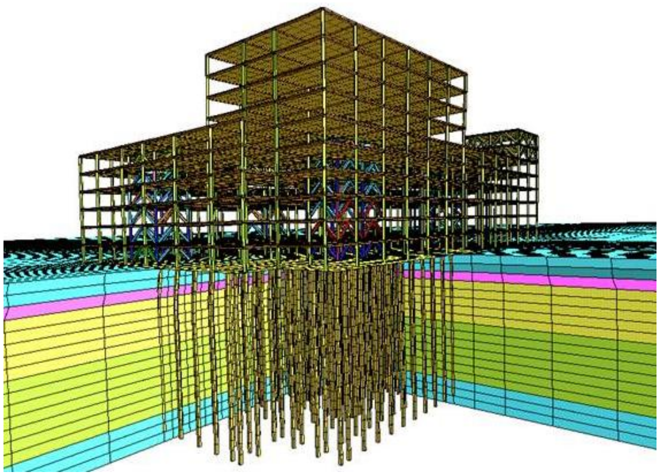
NIST GCR 14-917-27



Nonlinear Analysis Research and Development Program for Performance-Based Seismic Engineering

NEHRP Consultants Joint Venture
A partnership of the Applied Technology Council and the Consortium of Universities for Research in Earthquake Engineering

National Institute of Standards and Technology
U.S. Department of Commerce

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Cover image – Soil-structure interaction simulation model (courtesy of M. Willford)

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Prepared for
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By
NEHRP Consultants Joint Venture
A partnership of the Applied Technology Council and the
Consortium of Universities for Research in Earthquake Engineering

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Preface

The NEHRP Consultants Joint Venture is a partnership between the Applied Technology Council (ATC) and the Consortium of Universities for Research in Earthquake Engineering (CUREE). In 2007, the National Institute of Standards and Technology (NIST) awarded the NEHRP Consultants Joint Venture a National Earthquake Hazards Reduction Program (NEHRP) "Earthquake Structural and Engineering Research" task order contract (SB1341-07-CQ-0019) to conduct a variety of tasks. In 2011, NIST initiated Task Order 11174 entitled, "Analysis, Modeling, and Simulation for Performance-Based Seismic Engineering." The objective of this project was to develop a comprehensive, long-range research and development program to establish best-practice guidelines for practitioners to conduct nonlinear analysis, structural modeling, and computer simulation for seismic applications, and to support the ongoing the development and implementation of performance-based seismic engineering.

This work is an extension of NIST GCR 09-917-2, *Research Required to Support Full Implementation of Performance-Based Seismic Design*, in which several research topics were identified as high-priority in terms of fostering full development and implementation of performance-based seismic engineering. These included: (1) improvement in analytical modeling and demand assessment capabilities for buildings in near-collapse seismic loading; and (2) clarification and coordination in the translation of test results to currently used performance levels.

This project intends to advance the practice of nonlinear dynamic analysis so that it can be used more widely and with more confidence, enabling widespread adoption of performance-based seismic engineering. This entails addressing the gap between state-of-the-art academic research and state-of-the-practice engineering applications of nonlinear analysis, structural modeling, and computer simulation. It also entails improving state-of-the-art techniques to more reliably capture the full range of structural response than is currently possible with methods that are in use today. Taken as a whole, the program presents a suite of initiatives that, if implemented, would improve nonlinear dynamic analysis capabilities, and identify procedures that are suitable and attractive to practitioners, while maintaining levels of accuracy commensurate with research models.

The NEHRP Consultants Joint Venture is indebted to the leadership of Greg Deierlein, Project Director, and to the members of the Project Technical Committee, consisting of Peter Behnam, Finley Charney, Laura Lowes, Jonathan Stewart, and Michael Willford for their contributions in developing this report and the resulting recommendations. The Project Review Panel, consisting of C.B. Crouse, Jeremy Isenberg, Ali Karakaplan, Michael Korolyk, Bret Lizundia, Graham Powell, and Andrei Reinhorn provided technical review and comment at key developmental milestones during the project. The names and affiliations of all who contributed to this report are provided in the list of Project Participants.

The NEHRP Consultants Joint Venture also gratefully acknowledges Jack Hayes (NEHRP Director), Steve McCabe (NEHRP Deputy Director), and Kevin Wong (NIST Project Manager) for their input and guidance in the preparation of this report, Laura Samant for ATC project management, and Amber Houchen and Bernadette Hadnagy for ATC report production services.

Jon A. Heintz
Program Manager

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Introduction and Background

1.1 Project Objectives and Background

Performance-based seismic engineering (PBSE) is an essential element in the future of earthquake engineering analysis and design. Nonlinear dynamic analysis, which models the inelastic behavior that structures experience during earthquakes, is an important tool that enables engineering practitioners and researchers to employ PBSE.

The objective of this project is to advance the practice of nonlinear dynamic analysis so that it can be used more widely and with more confidence, enabling more widespread adoption of PBSE. Meeting this objective will entail addressing the gap between state-of-the-art academic research and state-of-the-practice engineering applications of nonlinear analysis, structural modeling, and computer simulation. It will also entail improving state-of-the-art techniques to more reliably capture the full range of structural response that occurs during earthquake shaking.

The purpose of this report is to outline a comprehensive, long-range *Nonlinear Analysis Research and Development Program*. This program identifies needed technical development activities and research to promote and improve the use of nonlinear analysis. The recommended initiatives range significantly in focus and ambition, encompassing the following broad topics:

- Identification and documentation of best-practices for nonlinear analysis methods in forms that are useful for building performance assessment and design by practicing engineers.
- Verification, validation, and calibration of nonlinear analysis software codes so that it is clear how well current analysis models simulate actual behavior of realistic building structures.
- Pursuit of fundamental research on important aspects of physical behavior that are not well understood or are unclear in terms of importance to design and analysis.
- Improvement in nonlinear analysis software functionality, including acceleration of computation times and improved interfaces for model inputs and results.

Taken as a whole, the program presents a suite of initiatives that, if implemented, would improve nonlinear dynamic analysis capabilities in procedures that are suitable and attractive to practitioners, while maintaining levels of accuracy commensurate with research models.

This work builds on NIST GCR 09-917-2, *Research Required to Support Full Implementation of Performance-Based Seismic Design* (NIST, 2009a), in which several research topics were identified as high-priority to foster full development and implementation of PBSE. These included: (1) improvement in analytical modeling and demand assessment capabilities for buildings in near-collapse seismic loading; and (2) clarification and coordination in the translation of test results to seismic performance levels.

The recommended research and development program does not promote analysis for the sake of analysis. Rather, the focus is on analysis capabilities that will advance earthquake engineering practice in meaningful ways. An underlying question to consider is the level of analytical sophistication that is necessary and cost-effective for use in engineering practice. Related to this question is the issue of software availability, including the capabilities of both commercial and research software that are available to practicing engineers and amenable to design.

The immediate focus of the program is on analysis software tools, both commercial and research software, that are currently available or likely to become available for practice in the near future. The program also explores important needs to help establish a roadmap for next-generation analysis capabilities. These may require longer-term research efforts to develop fundamental models with computational methods that take full advantage of emerging cloud-computing technologies.

1.2 Approach to Program Development

The approach for developing this report and the recommended research and development program has been to:

- Outline a vision for the use of nonlinear analysis in seismic analysis and design, both in the near term and longer term, and identify the obstacles and challenges to achieving this vision.
- Identify critical research and development needs that, when addressed, can lead to improved use of nonlinear dynamic analysis for PBSE, including the publication of a series of nationally accepted guidelines for conducting nonlinear analysis, structural modeling, and computer simulation for seismic applications.
- Identify and describe potential research initiatives that meet the identified research and development needs and contribute to attaining the defined vision. These include understanding, evaluating, and recommending best practices for solving nonlinear structural analysis problems. They also involve assessing the level of sophistication required to accurately model a structure undergoing

nonlinear dynamic response in an earthquake, and the level of detail necessary to accurately model material and geometric nonlinearity as the structure responds from initial yield through the onset of collapse.

1.3 Organization and Content

This report provides a synthesized research and development program to improve the effective use of nonlinear dynamic analysis for performance-based seismic engineering.

Chapter 2 reviews the relationship between nonlinear analysis and seismic design, including the motivation and goals for performing nonlinear analysis. It describes the current status of nonlinear analysis in earthquake engineering practice and earthquake engineering research, and provides a comparison with state-of-the-art nonlinear analysis in other fields of science and engineering. A vision for the future of nonlinear analysis in design is described, in both the near term and longer term, along with a summary of anticipated challenges for achieving this vision.

Chapter 3 outlines a series of initiatives related to verification, validation, and calibration procedures to promote the development and implementation of more accurate nonlinear analyses and software codes.

Chapter 4 describes initiatives related to modeling capabilities that are intended to improve understanding of nonlinear behavior, improve mathematical modeling of materials and components, and inform explicit consideration of uncertainty. Initiatives range from fundamental research to an emphasis on implementation.

Chapter 5 presents initiatives related to computational technologies to address model formulations and software implementation to improve the speed, utility, and functionality of analytical tools.

Chapter 6 outlines initiatives for developing analysis guidelines and example applications to facilitate the use of nonlinear analysis in design practice, and for developing a framework for acceptance criteria for use with nonlinear dynamic analysis.

Chapter 7 summarizes the overall scope of the recommended research and development program, provides an order-of-magnitude estimate of the budget, and presents a schedule in terms of the relative timing of individual research initiatives. It includes discussion of collaboration with other organizations, and long-term research needs and opportunities for fundamental advancements in modeling and simulation technologies.

A list of references cited and a list of project participants are provided at the end of this report.

Chapter 2

Vision for Use of Nonlinear Dynamic Analysis

The research and development recommendations in this report stem from a vision of how nonlinear dynamic analysis could be used in engineering practice for performance-based seismic engineering. By clarifying desired outcomes, this vision points towards initiatives needed to bridge the gap between today's usage and the future potential of nonlinear analysis. This chapter reviews how nonlinear analysis is currently used in earthquake engineering practice and research, as well as in other fields. It then describes a vision, which is an articulation of how nonlinear dynamic analysis could be used in the near-term (five years) and in the longer-term (ten to fifteen years). It concludes with a summary of obstacles that must be overcome, through focused research and development activities, in order to achieve this vision.

2.1 Role of Nonlinear Analysis in Engineering Practice

Nonlinear analysis requires significantly more effort than elastic analysis. Although the use of nonlinear analysis is increasing in engineering practice, it is usually only applied when there is clear motivation, such as in unique design situations. Four areas that provide motivation for the use of nonlinear analysis in earthquake engineering practice are:

- **Evaluation and Retrofit of Existing Buildings.** Most existing buildings fall short of meeting prescriptive detailing requirements in codes and standards for new buildings, which presents a challenge for evaluation and retrofit using code-based elastic analysis methods. As a result, seismic evaluation and retrofit of existing buildings has been one of the primary drivers for the use of nonlinear analysis in engineering practice. Engineering resource documents such as FEMA 273, *NEHRP Guidelines for the Seismic Rehabilitation of Buildings* (FEMA, 1997) and ATC-40, *Seismic Evaluation and Retrofit of Concrete Buildings* (ATC, 1996), and successor documents such as FEMA 440, *Improvement of Nonlinear Static Analysis Procedures* (FEMA, 2005) and ASCE/SEI 41-06, *Seismic Rehabilitation of Existing Buildings* (ASCE, 2007), introduced the notion of performance-based limit states and provided the first comprehensive guidance on the use of nonlinear analysis in design.
- **Performance-Based Design of New Buildings.** Although most new buildings are designed using elastic analysis methods and prescriptive code provisions, the

use of nonlinear analysis in the design of new buildings is becoming more common to: (1) demonstrate code equivalence for structural systems or components that do not meet prescriptive code requirements; and (2) assess and provide building performance that is at or above the level expected of standard code designs. The design of tall buildings with seismic-force-resisting systems that are not permitted by the code (e.g., shear wall-only systems that are taller than 160 feet in height) is a common example of the use of nonlinear analysis in design. Engineering resource documents such as the Pacific Earthquake Engineering Research Center (PEER) *Guidelines for Performance-Based Seismic Design of Tall Buildings* (PEER, 2010), the Los Angeles Tall Buildings Structural Design Council (LATBSDC) *An Alternative Procedure for Seismic Analysis and Design of Tall Buildings Located in the Los Angeles Region* (LATBSDC, 2011), and the Council on Tall Buildings and Urban Habitat (CTBUH) *Recommendations for the Seismic Design of High-Rise Buildings* (CTBUH, 2008) outline explicit requirements for the use of nonlinear dynamic analysis to assess the performance of tall buildings. FEMA P-58-1, *Seismic Performance Assessment of Buildings, Volume 1 – Methodology* (FEMA, 2012b), is a resource that uses nonlinear analysis in the probabilistic assessment of the seismic performance of buildings, which is not specifically related to tall buildings.

- **Improvement and Calibration of Design Standards.** Nonlinear dynamic analysis is being used to calibrate seismic design standards for consistent performance across different structural system types. FEMA P-695, *Quantification of Building Seismic Performance Factors* (FEMA, 2009d) outlines procedures for assessing the collapse risk of buildings using nonlinear dynamic analyses. Idealized building collapse fragility curves based on the criteria contained in FEMA P-695 were used to develop risk-targeted seismic design maps that have been incorporated into ASCE/SEI 7-10, *Minimum Design Loads for Buildings and Other Structures* (ASCE, 2010).
- **Seismic Risk Assessment.** Since the introduction of HAZUS® and comparable seismic risk assessment methods in the late 1990s, procedures have been continually refined, including methods that employ building-specific analyses to improve building fragility models. *HAZUS®-MH MR5 Advanced Engineering Building Module* (FEMA, 2009b) is an example of guidelines for using building-specific nonlinear analyses in seismic risk assessment.

2.1.1 Demand and Acceptance Criteria

Before embarking on a nonlinear analysis exercise, it is important to clearly articulate the objectives of the analysis. For example, nonlinear analyses to establish equivalence with minimum code requirements for new building designs may differ from those for risk assessment of existing buildings. Clarifying the analysis objectives is the first step in defining demand parameters and associated acceptance criteria through which performance will be evaluated. The definition of demand parameters, in turn, establishes requirements for the model to ensure that the demand parameters can be reliably determined from the analysis.

Building drifts and story drift ratios are commonly used demand parameters because they are considered to provide a more reliable measure of the overall behavior and performance of structural and nonstructural components (FEMA, 2012b; PEER, 2010). Reported drifts may include both peak drift and residual drift, with residual drift being particularly important for assessing post-earthquake functionality, feasibility and cost of repairs, and restoration time.

In addition to building drift, local demand parameters can be used to evaluate the performance of individual components. For structural components, local demand parameters are generally distinguished between deformation-controlled and force-controlled actions, depending on the governing characteristics of the component. For *deformation-controlled* components, demands are based on a measure of deformations or strains, which are compared against acceptance criteria that permit some level of inelastic response before degradation is expected to occur. For *force-controlled* components, demands are based on applied or induced forces, and the components are intended to remain essentially elastic to avoid undesirable damage or strength and stiffness deterioration. Although an effective convenience for practical design, the distinction between deformation-controlled and force-controlled components is not always clear, particularly in existing buildings or other structures where inelastic deformation in nonductile components is unavoidable.

In addition to drift, commonly used structural demand parameters for deformation-controlled components include:

- Rotations (total or plastic) in inelastic hinges of beams, columns, and other flexural members.
- Axial deformations or equivalent normalized axial strain in braces or struts.
- Generalized shear panel deformations in beam-column joints of steel and concrete moment frames.
- Longitudinal (fiber) strains in concrete and reinforcing steel in reinforced concrete shear walls. One of the challenges in measuring strain is establishing an appropriate gage length that allows consistent reporting and comparison of strains to the governing acceptance criteria. Similar measures are sometimes used for reinforced masonry shear walls.
- Concentrated deformations in inelastic springs (axial, shear, or rotation) that are used to model and evaluate nonlinear response of foundations, soil-structure-interaction effects, and inelastic collectors.

Usually component deformation parameters are reported and evaluated based on peak quantities (i.e., peak hinge rotations or peak strains); however, with the increasing use of nonlinear dynamic analysis (in contrast with static pushover analysis), arguments can be made for considering cumulative deformation measures to distinguish between load history effects in evaluating demands and acceptance criteria. There are also some components that may be sensitive to other deformation-related demands, such as viscous dampers, in which velocities are an important design parameter.

Demand parameters for force-controlled components typically include the axial force, shear, or moment (or some combination of these) developed in the component. In some cases, maximum stresses may be reported in lieu of forces although, as with strain measures, consideration must be given to the characteristic area over which stresses are determined. The force or stress demands are typically compared to the strength of the component in question, which is determined using nominal strength equations from building codes or material design standards. Although the definition of demands for force-controlled components seems straightforward, in some cases there are unresolved questions as to whether peak force demands (or peak stresses) are a realistic measure for evaluating overload and failure of a component. For example, large spikes in high frequency loading can exceed the static strength of a component, but these spikes may be so short in duration that significant yielding or damage does not occur. How large-magnitude, short-duration forces should be treated is one of several open questions related to the calculation and interpretation of demands in force-controlled components.

For performance-based design of buildings, other parameters may be needed to assess the performance of nonstructural components, including architectural cladding and partitions, mechanical and electrical systems, and building contents. Demand parameters for nonstructural components are differentiated between deformation-sensitive and acceleration-sensitive components. Examples of deformation-sensitive components include partition walls, cladding, glazing, and other systems, in which damage is correlated to imposed story drifts. Acceleration-sensitive components include ceiling systems and building contents, in which damage is correlated to forces generated by peak floor accelerations.

2.1.2 Model Types

Nonlinear structural analysis models can vary significantly, where the appropriate choice of model depends on the type of structural material and system, the analysis objectives and required demand parameters, the ability of available models to reliably capture the governing behavioral effects of the structure, and available resources in terms of human capital (time and effort) and computational tools (analysis software and computing capabilities).

Figure 2-1 shows an example of the various types of structural component models used to simulate beam-column behavior. At the left are concentrated plasticity (plastic hinge) models, in which all of the nonlinear effects are lumped into an inelastic spring characterized by a single-degree-of-freedom (e.g., moment-rotation) or a multi-axial spring. At the right of the figure is a detailed continuum finite element model, which might include explicit three-dimensional representations of all components. In between are various types of distributed plasticity fiber elements providing hybrid representations between the extremes of finite element and concentrated plasticity. To some extent, all of the models have a phenomenological basis because they all ultimately rely on mathematical models that are calibrated to mimic nonlinear phenomena observed in tests. However, the concentrated plasticity models rely almost exclusively on phenomenological representation of the overall component behavior, while the continuum finite element models include a more fundamental representation of the behavior where (in concept) only the most basic aspects (e.g., material constitutive relationships and characteristic length parameters) rely on empirical data.

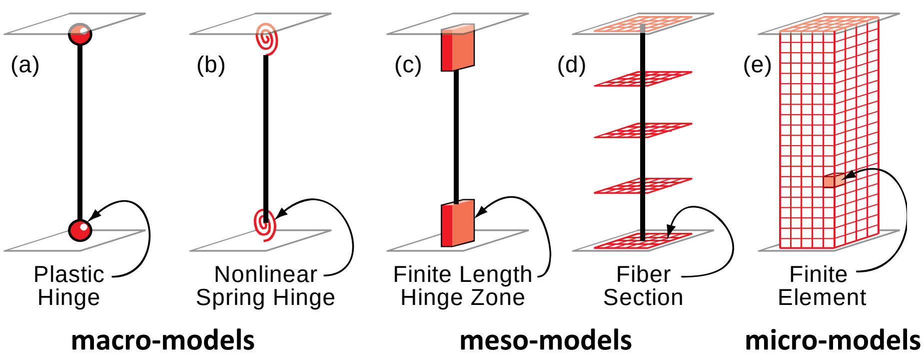

Figure 2-1 Types of structural component models (NIST, 2010d).

For modeling the overall response of beam-columns in steel or concrete moment frames, concentrated plasticity models can generally capture most of the important behavioral effects, from the onset of yielding up through significant strength and stiffness degradation associated with concrete crushing and reinforcing bar buckling (concrete members) and local flange and web buckling (steel members). In some ways, these highly nonlinear effects can be more reliably captured with simple hinge models than with finite element models. However, effects such as the interaction between axial, flexure, and shear failure in concrete members, or the interaction of local and torsional-flexural buckling in steel members, are difficult to capture using concentrated plasticity models. Fundamental finite element models can overcome some of the limitations of concentrated plasticity models in simulating the local and torsional-flexural buckling of steel members. However, finite element technology is not developed enough to accurately and reliably simulate other effects, such as concrete dilation under large cyclic strains, and the associated localized buckling and fracture of reinforcing bars in concrete members.

The choice between phenomenological models and fundamental models depends on several factors that ultimately balance practical design requirements with available modeling capabilities and resources. In determining the most appropriate model, the following points should be considered:

- How realistic are available analysis models in state-of-the-art research and leading-edge practice? How realistic do the models need to be for performance-based seismic engineering?
- Capacity design methods can be used to control or limit certain behaviors. As a result, design does not always require exact simulation of all modes of behavior. However, there are situations where it might be desirable to reliably simulate the response of buildings over their full range of response, up to collapse.
- The desire for accuracy and realism in the analysis model should be balanced against other unknowns and uncertainties. Uncertainty is not necessarily reduced when a more sophisticated model is used. There are factors in design and construction that affect performance in ways that are beyond the control of the engineering analyst.
- Although it is highly desirable to directly simulate response at a fundamental level, ultimately response must be validated to empirical test data at component, subassembly, and system levels. At what level of resolution (e.g., material, component, or subsystem) are the analysis models calibrated?

2.2 Current Status of Nonlinear Analysis

As background for future planning, it is instructive to consider the current capabilities of nonlinear analysis relative to how it is used in earthquake engineering practice, earthquake engineering research, and other scientific and engineering fields.

2.2.1 Earthquake Engineering Practice

Evaluation of Existing Buildings

Evaluation and retrofit of existing buildings was a primary driver in the development and application of nonlinear analysis in design practice. Formal procedures for nonlinear analysis of buildings were first established in FEMA 273 and ATC-40. These documents introduced the Coefficient Method and the Capacity Spectrum Method of nonlinear static analysis, utilizing a generalized force-deformation model (as shown in Figure 2-2) to describe the nonlinear response of common structural components. The component modeling parameters and acceptance criteria described by this force-deformation model were a major step forward in facilitating the practical use of nonlinear analysis in design. The procedures have since been refined in successor documents including FEMA 440 and ASCE/SEI 41.

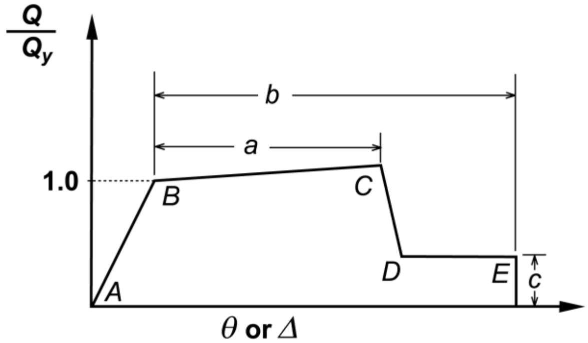

Figure 2-2 Generalized force-deformation model for component response (FEMA, 1997).

Although the concepts introduced in FEMA 273 and carried through ASCE/SEI 41 were an advancement at the time, the modeling parameters and acceptance criteria for nonlinear static (pushover) analysis have important limitations when applied to nonlinear dynamic analyses. Figure 2-3 shows a comparison between the response curve under a monotonically applied load (solid line) and the response envelope from cyclic test data (dashed line). The degradation observed in the cyclic response envelope (relative to the monotonic response) is not unique and depends heavily on the cyclic loading protocol that is applied.

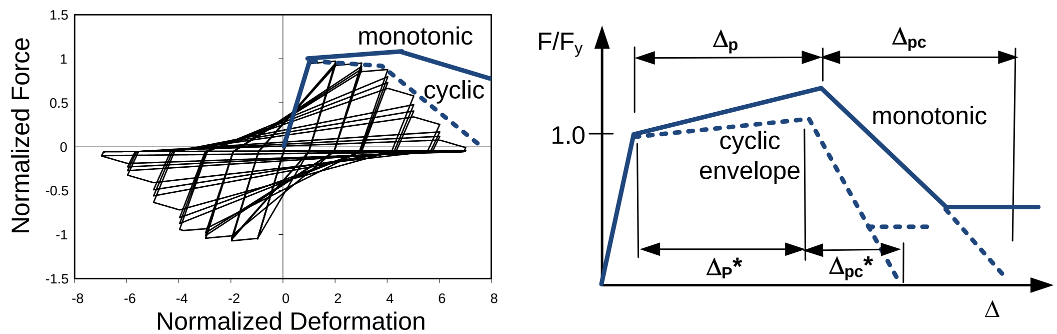

Figure 2-3 Monotonic versus cyclic response envelopes (ATC, 2010).

The generalized force-deformation curves in ASCE/SEI 41 are calibrated to the cyclic response envelope for components subjected to a standardized, symmetric loading history. Use of a fixed cyclic envelope curve is reasonable in static analyses, but is not adequate in dynamic analyses intended to use cyclic models to capture hysteretic damage and degradation effects directly in the analysis. Moreover, ASCE/SEI 41 generalized force-deformation curves are presented with single, deterministic values, without any information on the uncertainty or reliability of the parameters.

Tall Buildings

Similar to how FEMA 273 introduced the practical use of nonlinear static (pushover) analysis to the design profession, the PEER (2010) and the LATBSDC (2011) documents introduced practical use of nonlinear dynamic analysis in guidelines for seismic design of tall buildings. A related document, PEER/ATC-72-1, *Modeling and Acceptance Criteria for Seismic Design and Analysis of Tall Buildings* (ATC, 2010) provides detailed recommendations for nonlinear modeling, and performed a detailed review of modeling parameters and acceptance criteria for the cyclic response of steel and concrete system components. Together, these resources provide a methodology and procedures for establishing the equivalence of non-conforming seismic force-resisting systems to the performance intent of the prescriptive requirements in ASCE/SEI 7. In addition, they also provide recommended demand and acceptance criteria considering the effect of uncertainties in ground motions, modeling parameters, and material strengths. Although they represent a significant advancement, the component-specific criteria in these resource documents are not developed to the same level of detail and specificity as provided in ASCE/SEI 41.

Performance-Based Seismic Assessment

The FEMA P-58 methodology (FEMA, 2012b) represents an advancement in the implementation of performance-based seismic assessment (and design) by providing procedures to explicitly evaluate probabilistic performance metrics, including risk of damage, repair costs, repair time, building closure, collapse, and casualties. Although the FEMA P-58 methodology utilizes results from nonlinear dynamic analyses, it provides relatively little in the way of methods or procedures for conducting nonlinear analyses. Rather, it focuses on performance assessment using new performance metrics, and refers to other resources for more detailed guidance on analysis, including ASCE/SEI 41, FEMA P-695, and NEHRP Seismic Design Technical Brief No. 4, *Nonlinear Structural Analysis for Seismic Design, A Guide for Practicing Engineers* (NIST, 2010d).

Collapse Safety Assessment

The FEMA P-695 methodology is based on an evaluation of building collapse risk using nonlinear dynamic analysis. The FEMA P-695 methodology provides a consistent framework for organizing and interpreting the results of nonlinear dynamic analyses, but it does not provide detailed procedures for modeling and analysis of specific systems and components. The methodology introduces explicit parameters to account for uncertainties in design and analysis, and to address specific issues related to scaling of extreme (rare) ground motions for assessing collapse. By establishing specific collapse risk acceptance criteria (i.e., 10% probability of collapse, on average across all systems, given the occurrence of the Maximum

Considered Earthquake), FEMA P-695 has prompted significant research and development on building collapse simulation.

Analysis Software

In general, most (though not all) practical applications of nonlinear analysis rely on commercial structural analysis and design software. Commonly used production software in the United States includes: PERFORM 3D, *Nonlinear Analysis and Performance Assessment for 3D Structures* (CSI, 2013b); SAP2000, *Integrated Software for Structural Analysis and Design* (CSI, 2013c); ETABS, *Extended Three Dimensional Analysis of Building Systems* (CSI, 2013a); and LARSA 4D, *Advanced Software for the Analysis and Design of Bridges and Structures* (LARSA, 2013). These programs generally support the use of concentrated plasticity models (i.e., plastic hinges, inelastic springs) and, to some extent, fiber-type beam-column and flexural wall models. Although not common, some consulting firms utilize more advanced commercially available software, including: Abaqus (Dassault, 2013); ANSYS (ANSYS, 2013); DIANA (TNO, 2013); and LS-DYNA (LSTC, 2013).

2.2.2 Earthquake Engineering Research

Continuing improvements are being made in earthquake engineering research, both in analysis technologies (e.g., model formulations and computational implementations) and their application to assess the seismic performance of buildings and other structures. Areas of recent and ongoing research include:

- Improvements in modeling of strength and stiffness degradation of structural components and systems to permit direct simulation of collapse, including consideration of size effects and the ability to capture cyclic versus in-cycle degradation under large inelastic deformations (illustrated in Figure 2-4).
- Characterization of variability in calculated demand parameters, including the effect of variability in random ground motions (record-to-record uncertainty) and structural modeling uncertainties.
- Validation of nonlinear models against large-scale test data for: steel and reinforced concrete frame members; reinforced concrete, masonry and wood structural panel shear walls; and steel braced frames.
- Improved characterization of ground motion hazard, including: selection and scaling of recorded motions; development, validation and use of simulated ground motions; and characterization of the effects of near-source pulses and long durations.
- Improved modeling of soils, foundations, and soil-structure interaction, including highly nonlinear soil response and ground deformations, and studies to examine the significance of soil-structure interaction on structural performance.

- Characterization of residual drifts and implications on post-earthquake safety and functionality.
- Regional modeling of earthquake effects on large urban regions, using input from seismological earthquake simulations to propagate seismic waves through the earth's structure, including the effects of local geology, rock-soil strata, and terrain features.
- Use of nonlinear analysis to benchmark and assess the risk of existing structures and current building code provisions, improve seismic design standards, and develop and validate the performance of new structural systems or retrofit methods.

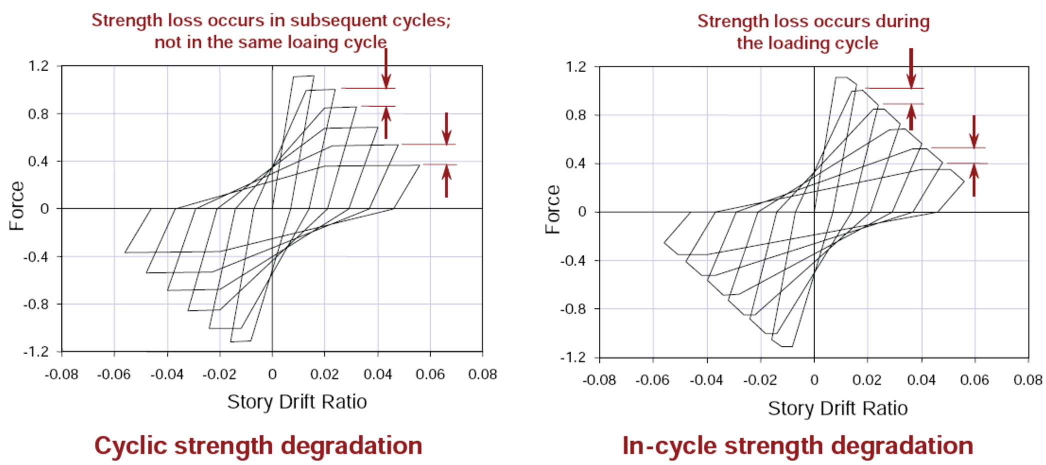

Figure 2-4 Cyclic versus in-cycle degradation (FEMA, 2005).

In addition to commercially available production software listed above, commonly used research software includes: OpenSees, *Open System for Earthquake Engineering Simulation* (OpenSees, 2013); Ruaumoko (University of Canterbury, 2013); IDARC 2D (University at Buffalo, 2013); ADINA, *Automatic Dynamic Incremental Nonlinear Analysis* (ADINA, 2013); and Zeus-NL (MAE, 2011).

2.2.3 Other Scientific and Engineering Fields

Although earthquake engineering presents unique and significant challenges for simulating the nonlinear response of complex buildings, it is useful to consider how other fields use detailed nonlinear finite element modeling. In some cases, earthquake engineering analysis has benefited from improvements that have been developed in other fields. It is also important to recognize where nonlinear analysis has facilitated advancements in engineering design that would not have been otherwise possible. Some of these fields include:

- The automobile industry and its extensive use of finite element analysis in design, manufacturing (metal forming), and assessment of crash worthiness for passenger safety.
- The aerospace and ship-building industries, which rely extensively on modeling of computational fluid dynamics, structural mechanics, and fatigue.
- Specialized civil engineering projects, including the assessment and design of large bridges, tunnels and other infrastructure, which involve extensive modeling of soils, foundations, and structures.
- The offshore oil industry, which conducts simulations of offshore oil platforms and facilities involving coupled fluid and structural models.
- The nuclear industry, which simulates containment buildings, piping, and other components subjected to both service and extreme loads.
- Industries with challenging and unique manufacturing processes, such as casting, and metal forming.
- Military and defense industries, which use nonlinear modeling to simulate the effects of blasts and ballistics on civil and mechanical structures.
- Geotechnical and seismological modeling of large rock formations for earthquake simulation, resource extraction (e.g., hydro-fracture for fracking), and other applications.

2.3 Vision for Nonlinear Analysis in Earthquake Engineering Practice

It is anticipated that nonlinear dynamic analysis, which allows analysts to more reliably capture the full range of structural response to earthquake effects, will play an increasingly significant role in in the future of performance-based seismic design of buildings. The goal of this research and development program is to provide a roadmap to enable this increased role through the advancement of nonlinear dynamic analysis in the following areas:

- *Verification, Validation, and Calibration*. There should be more accurate and reliable software that is rigorously verified and validated by comparison to well-vetted test data, analysis data, and field measurements.
- *Modeling Capabilities*. There should be improved modeling capabilities that accurately capture inelastic behavior, energy dissipation, and strength and stiffness degradation under large deformations, up to the onset of collapse.
- *Computational and Data Management Technologies*. There should be improved software that facilitates more effective use of analysis for design through quicker

turnaround times enabled by faster computations and closer integration between analysis, building information modeling, and data management systems.

- *Guidelines and Standards*. There should be comprehensive guidelines for all aspects of nonlinear dynamic analysis, enabling more reliable modeling of structures using micro-, meso-, or macro-scale models.

2.3.1 Near-Term Vision

In the near-term (i.e., five years) the overall vision is to facilitate more consistent and reliable use of nonlinear dynamic analysis methods for design that represent the current state-of-the-art in engineering research and practice, which includes improved knowledge and capabilities in the areas outlined below.

Verification and Validation of Analyses

Improved capabilities for validating nonlinear analyses, which will allow greater confidence in their use. Achieving this vision will require:

- Readily available test data sets and other supporting information that are vetted by professionals to establish the accuracy of current nonlinear analysis capabilities, including information on the major factors that influence the response and expected degree of uncertainty in the calculated response.
- Consistent procedures and criteria for software developers to validate nonlinear analysis capabilities and convey validation to users.
- Greater consistency in how test data are interpreted and used to validate analysis models.

Modeling Capabilities

Improved reliability in the use of existing nonlinear analysis technologies and awareness of their limitations. Achieving this vision will involve:

- Continued reliance on phenomenological macro-scale models (e.g., concentrated plastic hinges or inelastic springs) to capture nonlinear degrading response, but utilization of more realistic meso- and micro-scale models, where feasible and appropriate (e.g., concrete shear walls and specialized components).
- Focus on calculation of median (central tendency) response quantities, but with increasing capability to characterize ground motion and modeling uncertainties.
- Improved component models for cyclic and in-cycle degradation.
- Continued reliance on viscous damping to capture many sources of un-modeled energy dissipation, but with significant advances in understanding energy dissipation and how it is captured in nonlinear analysis.

- Improved knowledge and awareness of analysis model accuracy, as compared to real behavior of various structural components and systems.
- More realistic models for connections, foundations, and floor diaphragms, including kinematics that account for finite dimensions of structural components.

Computational and Data Management Capabilities

Greater utilization of the full capabilities available with modern computing technologies. Achieving this vision will be enabled by:

- Improved and streamlined tools to facilitate input and output of analysis data (e.g., visualization and querying of response) between analysis software and building information models (BIM).
- Standards to facilitate the creation of analysis models from three-dimensional BIM representations and interpretation of response through BIM technologies.
- Improved diagnostics to evaluate accuracy and numerical performance.
- Faster computation speeds to allow practical assessment of alternative designs (i.e., parameter sensitivity, larger numbers of ground motions, and automated processing of demand parameters).
- More robust solution algorithms that are less sensitive to numerical tolerances and reliably reach convergence.

Guidelines and Standards

Comprehensive guidelines to facilitate routine application of nonlinear dynamic analysis in design practice. Achieving this vision will include:

- Detailed guidance for modeling nonlinear cyclic response of structural members, connections, floor diaphragms and foundations (in contrast with current ASCE/SEI 41 requirements that are more suited to nonlinear static analysis).
- Detailed guidance for choosing appropriate parameters to capture un-modeled energy dissipation through viscous damping (i.e., Rayleigh, modal, or other viscous idealizations).
- Consideration of uncertainties in seismic demands and acceptance criteria.
- Characterization of seismic hazard, and selection and scaling of ground motions for nonlinear analyses.
- Interpretation and utilization of test data to validate modeling and design assumptions.
- Web-based resources that are continually updated to provide a summary of current knowledge, data, and best practices on the use of nonlinear analysis for design.

2.3.2 Longer-Term Vision

Over a longer-term horizon (i.e., ten to fifteen years), it is envisioned that there should be greater availability and access to computational models that capture behavior at more fundamental levels, and can accurately simulate structural response over a broader range of behavior, with less reliance on phenomenological calibration to component and subassembly models. Modeling behavior at more fundamental levels will enable more confidence in extending analysis models to large-scale structural components and systems that cannot be evaluated by testing. It is expected that improved capabilities will also facilitate innovation of new seismic force-resisting systems. Moreover, modeling technologies should evolve such that computational demands are less of a constraint, and it becomes more practical to evaluate alternative design solutions and modeling uncertainties through analysis. Achieving this longer-term vision will include improved knowledge and capabilities in the areas outlined below.

Verification and Validation of Analyses

- Fundamental models for a large variety of systems will have a high degree reliability, having been extensively validated against data for structural material, component, subassembly, and system tests.

Modeling Capabilities

- Practicing engineers will have ready access to a range of alternatives between fundamental macro-, meso- and micro-scale models as dictated by the specific situation, including validated models for wall structures, foundations, diaphragms, and new structural system innovations.
- There will be automated capabilities to characterize ground motion modeling uncertainties.
- Reliable and validated models will capture building response up to and beyond the onset of collapse, where all important degradation behavior is simulated directly in the analysis.
- Models will capture most of the energy dissipation in structural and nonstructural response, such that there is less reliance on viscous damping to capture sources of un-modeled energy dissipation.
- Models will be available to capture soil-structure-interaction, simulation of ground failure, and more realistic representations of site and foundation effects. The availability of improved foundation models will require commensurate advancements in how ground motions are applied in the computational models.

Computational and Data Management Capabilities

Automated tools will be routinely available to develop analysis models from design and construction information in three-dimensional BIM models, including:

- The ability to traverse seamlessly between global system and local subsystem and component model idealizations, including models built with different software platforms.
- Robust optimization tools to facilitate automated design using nonlinear analysis.
- The ability to conduct near real-time diagnostics of damage due to earthquakes or other extreme loading (e.g., system identification).
- Scalable computational algorithms and data management that take full advantage of parallel computing.
- Automated tools that ensure accurate convergence and avoid problems with numerical sensitivities and lack of convergence.

Guidelines and Standards

Guidelines and standards for nonlinear analysis will be comprehensive and will enable reliable modeling using micro-, meso- and macro-scale models, depending on the situation. The specificity of the guidelines and standards will be sufficiently clear to allow transparent implementation in commercial analysis software. Computing capabilities will be linked with online technical resources to streamline validation and calibration of results against consensus standards and professionally vetted data sets.

2.4 Obstacles to Achieving the Vision

Reaching the near-term and longer-term visions outlined above will require significant effort. Challenges associated with achieving these visions include:

- **Verification and Validation of Analyses.** Presently, there are no well-established guidelines or criteria against which to validate nonlinear analyses. In practice, engineers rely on modeling criteria in ASCE/SEI 41, which is based on a combination of limited test data and judgment. Although test data are available in published papers and reports, there are no established mechanisms for consistent interpretation of the data and validation of computational models. Anecdotal information from blind analysis competitions suggests that there are unacceptably large uncertainties (i.e., lack of reliability) in analytical predictions, though there is also speculation that many blind analyses, especially those that are set up as open competitions, are not an effective mechanism by which to evaluate software. A lack of well-vetted data and corresponding guidance for software validation are significant obstacles for widespread use and greater reliance on nonlinear dynamic analysis in design.

- **Modeling Capabilities.** Although significant advancements have been made in nonlinear modeling and simulation, there are still significant gaps and shortcomings in modeling capabilities for many types of structural components and systems. Even for steel and concrete moment frames, where hysteretic plastic hinge models are well developed, models are limited in their ability to reliably capture strength and stiffness degradation under large deformations considering interaction between axial and shear forces. In particular, models for concrete, masonry and wood shear walls, and steel braces (with buckling behaviors), are not well-developed.
- **Computational and Data Management Capabilities.** Despite significant advancements in computing technologies, computing speed and data management continue to present a bottleneck to effective use of nonlinear analysis in design. Realistic three-dimensional models of large buildings often require hours of computer time to complete a single nonlinear dynamic analysis. As a result, even the minimum ASCE/SEI 7 requirements for response history analysis (e.g., use of seven or more ground motions) become an obstacle to making effective use of nonlinear analyses in design, which can include iteration through multiple design options. Moreover, the required analysis times make it prohibitive to conduct larger numbers of analyses that would be required to accurately characterize uncertainties in response due to variations in modeling parameters, ground motions, and other factors. Apart from computational speeds, the lack of interoperability between analysis software and building information models (BIM) further hinders the effective use of nonlinear analysis as a design tool.
- **Guidelines and Standards.** At present, there are no comprehensive, well-vetted guidelines (or standards) for conducting nonlinear dynamic analyses. Engineers seeking to utilize nonlinear analysis in practice need to conduct project-specific research to develop appropriate criteria and substantiate analytical results to building departments and peer review teams.

The following chapters present a series of initiatives designed to make significant progress towards overcoming these challenges. Although the primary focus is on advancements that can be achieved in the near-term, it is expected that this work will serve to further motivate and formulate detailed plans to address the longer-term vision and opportunities for utilizing nonlinear analysis in seismic design.

Chapter 3
Verification, Validation, and Calibration

This chapter addresses issues related to assessing and improving the accuracy of nonlinear analysis and available software codes. Proposed research and development initiatives are related to the use of blind analysis exercises, the systematic verification, validation, and calibration of models, and the collection, development, and curation of benchmark test data.

3.1 How Reliable Are Predictions from State-of-the-Art Analysis Methods?

Three key questions to consider in assessing the need for improving nonlinear dynamic analysis for design are:

- With what degree of realism and reliability can designers and analysts currently predict the actual seismic performance of buildings?
- What are the practical consequences of limitations and inaccuracies in nonlinear dynamic analysis as they relate to design decisions?
- To what extent are limitations due to: (1) analysis models and software capabilities; (2) the skill and experience of the analyst; or (3) inability to simulate actual structural behavior?

The answers to these questions will identify areas where software enhancement, education and training, or additional experimental research would lead to meaningful improvement in nonlinear analysis for design. At present, the answers are not known. There does not appear to be any systematic study available in the literature that objectively assesses the adequacy of the outcomes produced by different analysts, predicting the seismic performance of a range of practical building types, using different software packages available to practicing engineers. Assessing the realism and reliability of analytical predictions (and the consequences for design) requires comparison with actual data on building performance under known seismic loading. In other words, it requires *validation*.

3.1.1 Reliability, Variability, Realism, and Accuracy

A fundamental objective of design for new buildings and retrofits of existing buildings is to meet target performance standards. Approved design methodologies are adopted by engineers to meet design targets with an adequate degree of reliability (although the actual degree of reliability in current methods has not been quantified). Results from nonlinear dynamic analyses are only part of the information used by engineers to achieve reliable designs. Given the uncertainty and variability inherent in the parameters that go into a set of response predictions, absolute accuracy in analysis results cannot be expected. Nonetheless, sound design decisions, and the corresponding achievement of a reliable and economic building stock, are based on the notion that predictive performance information is as realistic and reliable as possible.

Some attributes of *realism* include:

- prediction of deformation and force demands that are not biased high or low;
- the ability to predict significant softening and weakening of structures due to potentially contributing mechanisms; and
- the ability to identify imminent collapse.

Some attributes of *reliability* include:

- predicting similar, realistic outcomes for a given set of conditions with different analysts using different software packages; and
- an understanding of software and modeling assumption limitations so that response data are not used outside their range of validity.

3.1.2 Blind Prediction Exercises

One measure for validation of analytical procedures is blind prediction. In a blind prediction exercise, analysts do not know the real behavior of a structure, which has been observed or measured in an experiment or actual event, at the time that the analyses are performed. This provides an unbiased assessment of prediction capabilities because prior knowledge of physical behavior cannot be used to improve simulation results. Blind prediction is analogous to predictive analysis in design practice. In design, there is no opportunity to improve predictions based on the behavior of a structure that has not yet been built, so analysts must rely on prior experience, data, past successful modeling techniques, and existing software capabilities to develop best-estimate response data.

A number of blind prediction exercises have been performed in the past. Teams of analysts have been invited to predict the outcome of a shake table test, or the response of buildings measured in earthquakes, given knowledge of the building design and the nature of the applied ground motions. Many exercises have focused on components and subassemblies, while others have involved large, full-scale structural systems (OECD, 1996).

Anecdotal evidence from blind prediction exercises indicates that the scatter among predictive results is large, and the comparison with measured response and observed behavior (e.g., nonlinear mechanisms and failure modes) is not favorable. This suggests that, in practice, many predictions are unrealistic and the reliability is low.

It is usually beyond the scope of individual blind prediction exercises to evaluate sources of variation between analytical predictions and actual data, or to identify analytical procedures that appear to be consistently better (or worse) than others. Also, there is an element of chance in blind predictions (i.e., a lucky predictive result that comes close to matching actual response), which can distort any conclusions drawn from the accuracy of alternative analysis formulations. These factors tend to limit the usefulness of data from blind prediction exercises as a source for general improvement of analytical reliability.

3.1.3 Factors Affecting Blind Prediction Accuracy

The wide scatter that is often observed between analytical predictions and measured response data is influenced by many factors, including:

- the structural behaviors that occur, especially the degree of nonlinearity;
- the type of element, basic element formulation, hysteresis rules and other rules built into the element formulation, mesh refinement, or solution strategy that is adopted;
- the way in which input parameters are selected or calculated;
- the degree to which the actual response is sensitive to unknown factors (e.g., the loading sequence, or the sequence of ground motion cycles); and
- numerical solution, software coding, or code implementation errors that can cause inconsistent predictions for similarly defined problems.

Considering these diverse sources of variability, it is not a trivial exercise to identify the specific reasons why an individual analysis does not match actual response data, or why two different analyses predict different results. Accordingly, it is difficult to draw meaningful conclusions from limited sets of analyses because differences could arise from many possible sources, including whether or not the input parameters are characterized consistently, there is an error in the material model, the mesh is too coarse, or the nonlinear model is incapable of representing a particular behavior. Without an in-depth assessment of the features and limitations of each analysis, the effectiveness of blind prediction exercises and comparative studies is limited.

3.1.4 Differences Between Blind Prediction and Analysis for Design

The conditions that apply for predictive analyses used in design are analogous to, but different from, conditions represented in blind prediction exercises. Possible differences include:

- The purpose of nonlinear analysis in design is to predict maximum response quantities (or a range of response quantities) for developing a robust design, rather than to match a specific set of response quantities.
- Nonlinear analyses performed by practitioners are often peer-reviewed, and might include sensitivity studies.
- Actual material properties are variable in the design of new structures, and can be unknown in the assessment of existing structures.
- Suites of hypothetical ground motions are used to obtain statistical measures of demand parameters (rather than a specific ground motion that is used to match an actual response).

In addition, specimens used in blind prediction tests typically do not include a number of features that affect response in real structures, such as:

- cladding and other nonstructural elements;
- structural components that are not part of the main seismic force-resisting system;
- foundation and soil flexibility; or
- the presence of structural irregularities dictated by the architectural configuration of real buildings.

Analysis to more accurately simulate the real response of structures should consider the presence of the features listed above. Blind prediction tests that do not include these features have limited ability to inform the accuracy or reliability of analyses that attempt to capture their effects. Often, such features are also ignored in analysis models for design, but design applications include provisions to safeguard against analytical simplifications that limit the accuracy of response predictions (e.g., redundancy or irregularity requirements, or restrictions on the use of modeled period versus code-specified period). Such safeguards are intended to limit the sensitivity of a design to special features or individual ground motions.

3.1.5 Learning from Blind Prediction Exercises

Despite some limitations, careful and detailed review of previous blind prediction exercises can yield important insight and information regarding the accuracy and reliability of nonlinear analysis methods. Research Initiative 3.1 targets learning from blind prediction exercises.

Proposed Research Initiative 3.1	
Title	Assess Reliability of Current Nonlinear Analysis Methods by Examining Blind Prediction Exercises
Objectives	• Identify the reliability with which analysts using current structural simulation tools can predict the observed nonlinear seismic response of structural systems by examining the results of previous blind prediction exercises. • Identify analysis techniques and assumptions that consistently produce superior (and inferior) correlations to physical tests. • Identify high-priority issues for future research efforts.
Scope	Task 1: Perform a systematic literature review of prior blind prediction exercises. Describe the experiments performed, the information provided to analysts, the analysis methods used, and the principal results. Select a number (e.g., six to ten) of these tests for detailed evaluation. The selected exercises should be relatively recent, cover a range of practical structural forms, and include both component and system tests. Task 2: For each blind prediction exercise, select appropriate engineering demand parameters (consistent with those used in practice for design) by which the realism of each simulation will be assessed. Categorize the simulations in relation to current best practice. After eliminating those that clearly do not represent the state-of-the-art, assess the variability of the remaining predictions. Identify any common factors that appear to result in good (or poor) accuracy and any behaviors that are important for simulations to capture in order to be reliable for design. Task 3: Collate the findings from the selected blind prediction exercises to draw overall conclusions. Prepare a list of features (structure types, behavior types, modeling assumptions) for which current methods appear most reliable and identify those which are least reliable. Identify the most appropriate means to improve reliability in each case (e.g., education about best practice, software enhancement, or further experimental data). Task 4: Identify the principal differences in new building design and evaluation/retrofit that are absent in blind prediction exercises. Discuss the extent to which these differences are beneficial (reduce uncertainty) or detrimental (increase uncertainty), and propose measures to minimize uncertainty.
Estimated Timeline	Approximately 24 months; tasks could be undertaken by teams of investigators working in parallel
Team	Researchers (faculty and graduate students) in close collaboration with engineering practitioners
Audience	NIST program planners; engineering practitioners; researchers
Product	Report

In general, shake table tests of significant structural assemblies (i.e., tests representative of real structures) should be the primary focus of investigation, although other selected tests (e.g., tests of subassemblies or components) may also be appropriate to include. Full-scale field data of building response in real earthquakes could also be considered, provided that sufficient information on the structural design and ground motions at the site are available. To help ensure that the conclusions are as relevant as possible to situations encountered in design practice, assessment of blind prediction exercises should require the involvement of design professionals.

Blind prediction analyses used in Research Initiative 3.1 should be screened by the team considering:

- Meaningful metrics, from a design practice point of view, by which the accuracy of the analyses can be judged.
- Analyses that are consistent with what is typically used in design practice; analyses that would not meet the standards employed in peer-reviewed practice; and analyses that are more advanced than would be used in practice.
- Variability observed in analyses that were performed in accordance with typical design practice, and subject to appropriate verification.
- Analyses that predicted the measured response most accurately.
- Common features of the most realistic analyses for each test.
- Major aspects of structural behavior that are commonly misrepresented, or represented inadequately in modeling.

Review of blind prediction exercises should examine a variety of structural system and material types. Such a review is expected to identify those systems and behavior types for which improvements in analytical representation are most needed, and those where current techniques, when properly applied, can provide realistic and reliable predictions of response.

3.2 Tiered Approach to Verification, Validation, and Calibration

3.2.1 Definitions and Past Experience

Several disciplines within earthquake engineering face similar challenges in evaluating the accuracy and reliability of complex dynamic computations. Examples include nonlinear geotechnical ground response analysis, nonlinear soil-structure interaction, and seismological ground motion simulations. In each of these cases, coordinated efforts have been undertaken to gain confidence in analytical predictions by checking each building block of the prediction methodology, and its software implementation, using a consistent and repeatable methodology.

Prior efforts share a common tiered approach of *verification*, *validation*, and *calibration*. The first tier is v*erification*, which involves comparing predictions from different analysis procedures for a simple and well-defined problem, or in some cases, testing model predictions against certain known solutions. A possible verification tool for structural engineering applications is checking the numerical material model for an individual element against its theoretical performance. The performance of the model under conditions producing a linear response, including proper treatment of damping, can be checked against frequency-domain solutions, which are exact for this case.

The second tier is *validation*, which involves comparison of analysis predictions to data. Ideally, validation should be combined with clear and transparent selection protocols for the parameters used in the analysis. Validation is different from blind prediction in that the analyst has the test results or field performance data as the analyses are being performed.

A well-performed validation effort employing predefined parameter selection protocols can lead to a certain degree of bias (i.e., misfit between the mean of model predictions and measured data). The third tier is *calibration*, in which poorly constrained parameters are adjusted in a transparent and repeatable manner to remove bias in model predictions.

3.2.2 Typical Validation Approach in Current Structural Engineering Research and Practice

A complete, tiered approach, including verification, validation, and calibration, is not typically used in the solution for seismic structural engineering problems. More typically, available data are used as a guide to the analyst and designer in modeling the expected response.

Consider the availability of data from appropriate testing (e.g., FEMA, 2007) of key structural components (e.g., shear walls or beam-column assemblies), that could be used to guide the assessment of an overall structural system. Typically, an analyst will validate the model against available tests. However, because the model is often adjusted to match the data, this process is a combination of validation and calibration. The resulting model is then used to provide response predictions over a range of conditions, often extrapolating beyond the range of the validated data set. This approach has several shortcomings, including the following:

- By circumventing the verification stage, misfits (i.e., differences in response quantities) between the model and the data that are caused by details of the model (e.g., coarseness in the mesh) might be incorrectly accounted for in the validation and calibration process (e.g., through a change in material properties).
- If available tests have not captured a failure mechanism that could be important in the real system (e.g., a buckling mode leading to cyclic degradation), the resulting model is likely to be unable to capture the physical behavior.

3.2.3 Types of Input Parameters and Their Role in the Tiered Approach

Some input parameters used in analysis software codes have a clear physical meaning. These parameters can be estimated by various means, and in some cases, measured by tests. Examples include the yield strength of steel reinforcing bars, the slip on a fault used in seismological simulations, and the shear modulus of soil used in soil-structure interaction analyses.

Other parameters are less clearly associated with a defined physical phenomenon and are often construed as correction factors for bringing a particular method of analysis into agreement with validation or calibration data. Examples include the crustal quality factor, Q, used in ground motion simulations, the ratio of effective to maximum shear modulus used in equivalent-linear geotechnical analyses, and the common adoption of 5% equivalent viscous damping in the seismic analysis of structures.

Parameters that are not directly related to physical phenomena are most often used in calibration because there is usually no other viable way of determining them. As a general approach, however, it is better to work towards increased use of physical parameters in defining analysis model attributes. Use of parameters without a physical meaning obscures the clarity and transparency of results, and impedes long-term development, especially when assumed values for key parameters become entrenched in practice and culture.

3.2.4 Implementation of the Tiered Approach

The tiered approach for verification, validation, and calibration, has been useful in identifying bugs in the coding of software (during verification) and in guiding the development of parameter selection and code usage protocols (during validation and calibration). When implemented, the tiered approach should be undertaken by large, multi-investigator teams. The team leader should be familiar with the fundamentals of the methods of analysis being considered, but should not be a proponent of any particular software or analysis methodology. The team should be composed of experts in the alternative methods of analysis under consideration, ideally including current developers and maintainers of respective software codes. Team members should be willing to commit the time and effort necessary to participate in the exercise, and to conduct software bug-checking and related work.

The process begins with verification. Suitable verification problems to test appropriate aspects of the software code should be identified and agreed upon. Past verification examples include:

- Comparison of simulated ground motions from multiple software codes for a simple crustal model and source function, as shown in Figure 3-1. The comparison illustrated in the figure is an example of a good match.
- Comparison of nonlinear moment-curvature relationships from alternative methods of soil-structure interaction modeling, as shown in Figure 3-2. In this case, the analyses showed notable differences that were ultimately explained by the varying assumptions within the methods.
- Comparison of peak story drift ratios from nonlinear dynamic analyses conducted with alternative beam-column formulations (e.g., distributed fiber-type elements

versus concentrated hinge-type elements), as shown in Figure 3-3. In this case, the initial stiffness of the concentrated hinge elements was developed through an independent parameter calibration with test data. In this sense the comparison is not a pure verification, but since the parameter calibration of the hinge models was performed independent of the fiber models, the match between the results for the two component formulations verifies that each method is working properly.

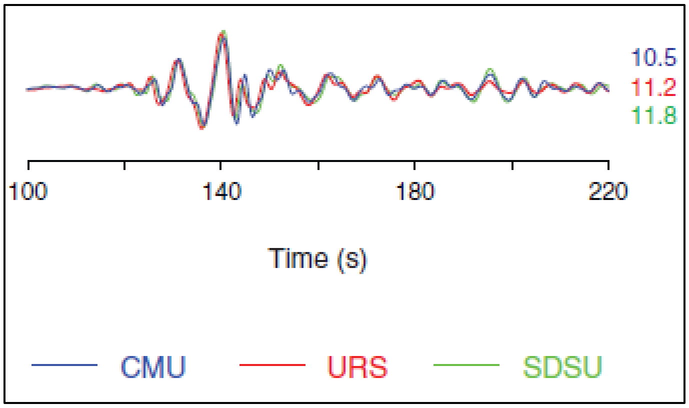

Figure 3-1 Comparison of velocity waveforms from three simulation methods for a common source and path (Bielak et al., 2010, with permission).

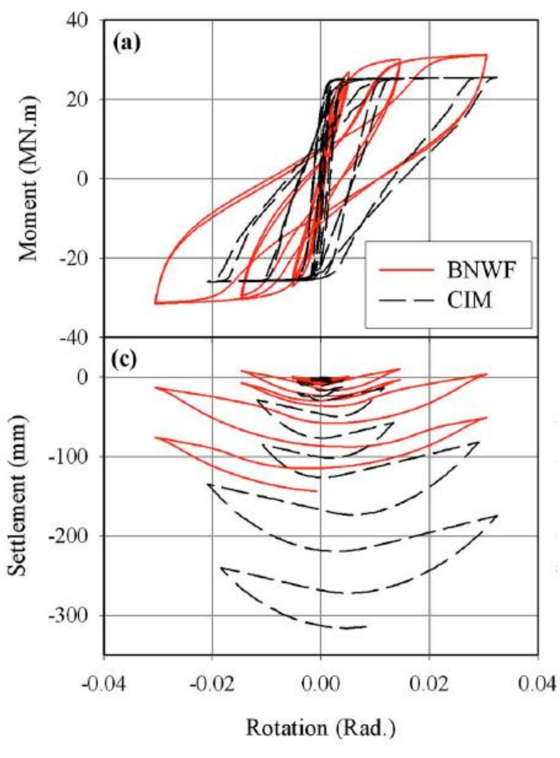

Figure 3-2 Comparison of moment-curvature and settlement-curvature relations computed using two simulation methods for a common footing and soil condition (Gajan et al., 2010, with permission from the Earthquake Engineering Research Institute).

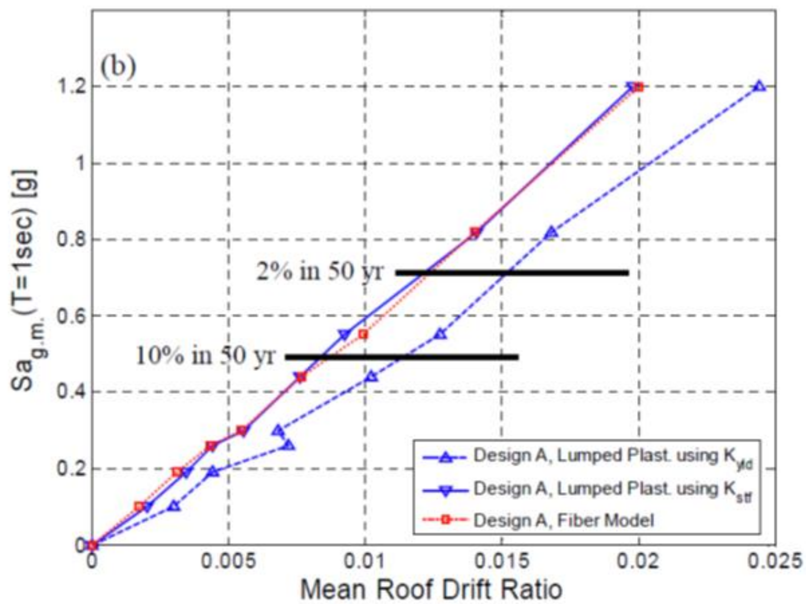

Figure 3-3 Comparison of median peak story drift ratios in a four-story concrete building, calculated by nonlinear dynamic analysis using fiber-type and concentrated hinge-type beam-column formulations (Haselton and Deierlein, 2007, with permission).

In the above examples, the favorable comparisons shown in the figures are the end result of a process that began with initially divergent results, and involved a significant degree of debugging. Another method of verification is to compare computed responses to a theoretically exact solution, which has been undertaken, for example, in various problems related to input motions and damping for nonlinear ground response (Kwok et al., 2007).

Once the performance of applicable software codes has been verified, it is necessary to develop consistent protocols for developing input parameters so that there is consistency between codes. Applicable data must then be gathered to start the validation stage. If a software code has already undergone some degree of validation and calibration, the compiled data set should include fresh data that has not been previously considered.

The validation process compares analytical predictions to measured test or field data. Predictions should be based on verified analysis software, and should follow established parameter selection protocols. Differences should be reported along with the applicable range of the validation. To the extent possible, validation should occur against a wide range of physical tests. In principle, demonstration of reliability to predict a particular type of behavior requires successful simulation of many different tests in which the subject behavior is exhibited. The more behaviors that are relevant to a particular type of response, the greater the number of validations that are needed.

Figure 3-4 shows a validation example comparing peak ground acceleration intensities that were obtained from simulations and observed (i.e., recorded) in the 1989 Loma Prieta earthquake. In this figure, the comparison shows much lower dispersion in the simulated data (identified as “sim”) relative to the observed data (identified as “obs”). Additional examples of validation related to nonlinear soil-structure interaction and nonlinear site response are presented by Gajan et al. (2010) and Kwok et al. (2007), respectively.

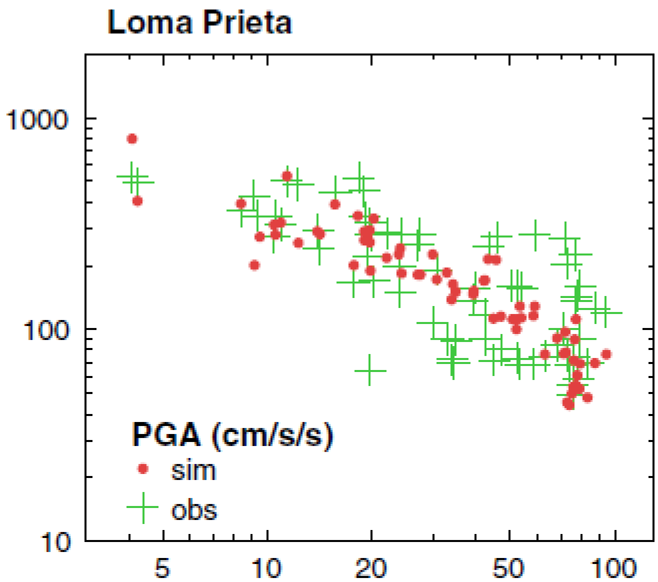

Figure 3-4 Comparison of peak accelerations versus distance (in km) between simulations and observed 1989 Loma Prieta earthquake data. (Graves and Pitarka, 2010, with permission).

Validation following established parameter selection protocols will often reveal misfits between simulation results and measured data. Typically, misfits will take the form of bias (difference in the mean) or variable levels of dispersion. The calibration stage of the tiered approach is intended to remove identified biases. One example of distinct validation, followed separately by calibration, pertains to a broadband simulation code in which misfits identified through validation (Star et al., 2011) were removed through a separate calibration process (Seyhan et al., 2013).

There are relatively few examples of formal calibration in the literature because calibration often occurs informally during validation. As comparisons are made between model results and observed data, the model or parameter selection protocols are adjusted to remove misfits so that the validation can be reported as successful. For this reason, analysts should be encouraged to use distinct and well documented validation and calibration stages. Research Initiatives 3.2a and 3.2b are related to the identification and use of distinct stages of the tiered approach for verification, validation, and calibration.

Proposed Research Initiative 3.2a	
Title	Develop Best Practices for a Tiered Approach for Verification, Validation, and Calibration of Software
Objectives	Develop a formal methodology for evaluating the reliability of structural simulation tools through the three-step verification, validation, and calibration process.
Scope	Task 1: Conduct a literature search on verification, validation, and calibration efforts in structural analysis and other fields. Task 2: Develop best practices guidelines for validation, verification and calibration of nonlinear analysis methods used in structural engineering. These should include guidelines for planning and utilizing tests for validation and calibration (see also Research Initiative 3.4).
Estimated Timeline	6 to 12 months
Team	Small team of researchers
Audience	Software developers and researchers; analytical experts from engineering practice
Product	Guidelines

Proposed Research Initiative 3.2b	
Title	Apply the Tiered Approach for Verification, Validation, and Calibration to Software
Objectives	Conduct a trial implementation of the three-step verification, validation, and calibration process to illustrate the value of the approach in terms of identifying bugs and limitations in applicable software codes.
Scope	Task 1: Apply the best practices guidelines developed in Research Initiative 3.2a to a set of analysis codes for selected structural components and systems for which good benchmark test data are already available. Selection of components and systems may require close coordination with benchmark data collected through Research Initiative 3.4, and should include an appropriate range of modeling techniques (e.g., macro-, meso- and micro-scale). Potential topics include: (1) seismic isolators; (2) steel braced and unbraced (moment) frames, including effects of joints; (3) reinforced concrete shear walls or frames; and (4) foundation systems. In the case of commercial software, this exercise can only identify limitations. Fixing commercial software bugs, or improving formulations to extend applicability, would require collaboration with, and buy-in from, commercial code developers. Task 2: Identify applicable limits on the analysis techniques investigated based on the validation/calibration data set. This task is related to Section 3.3.1. Task 3: Conduct a series of educational workshops to disseminate results and to receive feedback from the engineering community.
Estimated Timeline	24 to 36 months
Team	Research team (one or more faculty members and graduate students) running selected software, in collaboration with commercial software developers
Audience	Software developers; researchers; analytical experts from engineering practice
Product	Reports; possible revisions to software models and codes; educational seminars

3.3 Applications of the Tiered Approach

3.3.1 Identification of Limits in Nonlinear Analysis Techniques

A tiered verification, validation, and calibration approach, when properly implemented, should identify conditions where a given analysis model is unable to replicate certain aspects of material behavior or system response. For example, Yee et al. (2013) identified limitations in the ability of nonlinear ground response analysis procedures to accurately reproduce large-strain response in which the shear strength of the soil is being approached. The ability to identify such limitations, however, is limited by the available data set.

In structural simulations, consider the case of phenomenological models that represent nonlinearity in a backbone curve, but do not capture various degradation phenomena that produce variations in response as a result of different sequences of loading (e.g., cyclic and in-cycle degradation). Models neglecting these degradation phenomena are commonly used in practice. If such models were applied to a set of test data in which degradation was observed to occur, limitations in the ability of the models to simulate degraded behavior should become evident. There is obvious practical value in understanding the conditions under which a particular method of analysis becomes biased or unrealistic and, hence, should be avoided.

3.3.2 Selection of Appropriate Software for Use by Practitioners

If properly documented, results of a tiered approach could be used to assist in the selection of appropriate software codes for a given problem. It is anticipated that most analysis codes will have a range of conditions over which they are considered applicable on the basis of suitable validation and calibration. However, it would be extremely important to identify analysis procedures that frequently exhibit significant bias or cannot make realistic predictions beyond a certain demand level. The identification of such conditions would be useful in the evaluation of software reliability for particular classes of problems.

If a structural system is designed such that degradation is unlikely given the expected magnitude and number of cycles of earthquake shaking, then a degrading model is not necessary for predicting its performance. However, if the design earthquake is expected to produce cycles of demand that are sufficient to initiate degradation, the designer would be compelled, by clear statements of analysis software applicability limits, to consider a model that can account for degradation. Research Initiative 3.3 is intended to use the tiered approach in identifying software limitations and making software improvements.

The following attributes will allow models to be applicable over a wider range of performance:

- The ability to parameterize the shape of the backbone curve and hysteretic behavior (cyclic degradation of strength and stiffness) according to specific aspects of the designed component, accounting for potential physical degradation modes. Although bi-linear, elastic-plastic, or strain-hardening models may be adequate to represent the backbone curve for some highly ductile structural components, they will not be adequate for many others, particularly where buckling, fracture, cracking, or crushing of materials can arise.
- The ability to adjust behavior according to previous loading history, which is likely to be significant in cases involving buckling, fracture, cracking, or crushing of materials, and also where cyclic strain accumulation is important (e.g., low-cycle fatigue).

Proposed Research Initiative 3.3	
Title	Develop Improved Analysis Formulations and Software Based on the Outcome of a Tiered Approach
Objectives	• Address the weaknesses identified in Research Initiative 3.2b through targeted research leveraging the results of currently available test data. • Produce more robust analysis software that can be applied with greater confidence to a wider range of projects.
Scope	The specific scope will depend on the weaknesses identified in Research Initiative 3.2b. This initiative may involve theoretical development work in some cases, and, in other cases, will highlight testing needs to fill gaps in available data. This initiative will utilize benchmark data identified in Research Initiative 3.4. Shortcomings of simulation tools that cannot be addressed with analysis of existing data are to be addressed in Research Initiative 3.5. A suggested approach to overcome issues related to proprietary software is to develop and test new implementations in an open source platform (such as OpenSees), the details of which will be available to commercial developers who can choose to implement and test new analysis formulations in their own software codes. Results of this initiative will be documented in improved analysis software features that will be disseminated in workshops to practicing engineers.
Estimated Timeline	Depends on scope, but this is likely a major research initiative, which may extend beyond 3 to 4 years in duration; should be coordinated with testing in Initiatives 3.4 and 3.5, Chapter 4 initiatives, and (in some cases) longer term research.
Team	Research and commercial software developers
Audience	Software code developers; engineering practitioners
Product	Report; improved open source software codes; workshops

3.4 Use of Currently Available Test Data for Validation and Calibration

There is a large body of existing test data that could be used in validating and calibrating numerical codes for nonlinear structural response. A manageable, categorized, and quality-assured subset of this test data could be made accessible for benchmarking.

3.4.1 Data Types Necessary for Validation and Calibration

Validation is best approached in a step-by-step, component-by-component process. The idea is to validate individual building blocks of the system. It is, therefore, advisable to work with test data that is simple, and as directly related as possible to the aspect of the software that is being validated. This approach reduces the number of variables and uncertainties that must be addressed. In general, test data that are appropriate for validation and calibration will have the following characteristics:

- Tests are performed on an individual component with well-defined boundary conditions.
- Both monotonic and cyclic loading protocols are used.
- Tests are performed over a range of conditions (e.g., boundary conditions, specimen configurations) in which all significant behavior types are demonstrated.
- Tests are performed at appropriate specimen sizes, picking up scale effects, which may be especially significant for post-peak softening response.

Once individual components have been suitably validated, additional validation using tests of structural assemblies is valuable. Differences between tested and predicted response should be documented, and then followed up with calibration to remove bias. Calibration can involve adjustments to parameter selection protocols and details of the model formulation.

3.4.2 Classification of Available Data for Validation and Calibration

In general, validation and calibration should be performed separately for each type of structural component and system. A natural starting point for the classification of available data is by material and system type (e.g., steel moment frames, steel braced frames, concrete moment frames, and concrete shear walls). For each material or system type, ranges of important parameters that are relevant in a practical design and assessment setting should be identified (e.g., geometric parameters, material properties, and boundary conditions). For each material or system type, it is also important to identify the types of behavior that can significantly affect nonlinear performance of such systems in real earthquakes and tests. As an example, Table 3-1 presents the factors that might be identified in classifying tests for reinforced concrete shear walls.

The degree to which a specific test or test sequence is useful will depend on whether or not the aforementioned parameters are represented and the relevant behaviors are observed. For ease of use, the data and metadata from relevant testing programs should be available in digital form. Research Initiative 3.4 is intended to identify available data that is suitable for validation and calibration.

Table 3-1 Illustrative List of Possible Benchmark Test Parameters and Attributes for Reinforced Concrete Shear Walls

Parameters	Behaviors	Other Factors
Concrete, f_c'	Flexure, tension (ductile)	Loading protocol (e.g., monotonic, cyclic)
Steel reinforcing, f_y	Flexure, compression (non-ductile)	Type of test (quasi-static, shake table, field study)
Axial stress ratio	Shear, various modes	Completeness of data
Geometry	Flexure-shear interaction	
• thickness	Spalling	
• length	Bar buckling	
• flanges	Bar fracture	
• openings	Bond failure	
• discontinuities		
• coupling beams		
Detailing		
• boundaries		
• webs		

Published papers and online catalogues involving component tests, system tests, various loading protocols (quasi-static and dynamic), and scale factors (large-scale or small-scale) would be examined. Data that are inadequate or incomplete for the intended purposes would be rejected.

Proposed Research Initiative 3.4	
Title	Collate and Evaluate Existing Test Data Suitable for Validation and Calibration of Models
Objectives	• Create a systematic methodology to identify and screen existing test data that could be used to validate and calibrate specific types of structural system behavior. • Provide a model for continued data collection and screening. The data collected as part of this initiative should be coordinated with the validation and software improvement efforts of Research Initiatives 3.2 and 3.3.
Scope	Task 1: Conduct a literature review to identify existing published tests. For each test, evaluate the completeness of data and suitability for benchmarking. Categorize the physical characteristics and behavioral features exhibited in each test. Task 2: Identify a short list of tests recommended for validation of various features in software codes. Task 3: Identify a list of practical cases where inadequate test data are available.
Estimated Timeline	24 to 36 months
Team	Researchers and engineering practitioners
Audience	NIST program planners; building officials; engineering practitioners; software developers
Product	Report summarizing outcomes; website cataloging existing data

This classification exercise would seek to identify an adequate amount of high-quality test data relevant to each system category for comprehensive benchmarking purposes. The classification process would involve recording where each particular test fits into the parameter ranges, behavior types, and other factor categories.

The outcome of this exercise would include a list of tests that should be considered in a validation program for nonlinear analysis of different types of structural systems, and a list of topics (structural and procedural) where there is inadequate test data to cover the practical ranges of concern.

3.5 Best Practices and Critical Needs for Future Benchmark Testing

Results from Initiatives 3.2 and 3.4 can be leveraged to identify best practices and critical needs for additional testing to develop benchmark data for validation and calibration. Additional testing could range from quasi-static component tests to full-scale dynamic system tests (e.g., shake table tests).

Research Initiative 3.1 will reveal the strengths and weaknesses of system tests used in blind prediction exercises. The combination of Research Initiative 3.1 and subsequent initiatives will provide insight on needed system tests. Experiments for validating building blocks of numerical codes are likely to be relatively simple component tests. They should be focused on addressing theoretical uncertainties in simulation procedures for specific behaviors, and supporting the development of parameter selection protocols.

3.5.1 Cyclic Loading Protocols

Development and validation of nonlinear response models require data that characterize structural component response under a variety of cyclic loading histories. The majority of existing tests have been conducted primarily for the purposes of qualification testing, such as steel beam-column connection tests that were conducted to meet acceptance criteria specified by ANSI/AISC 341, *Seismic Provisions for Structural Steel Buildings* (AISC, 2010). Testing and cyclic loading protocols that are appropriate for qualification testing, however, are not necessarily appropriate for developing and validating nonlinear models.

Most qualification testing has been performed under uni-directional, quasi-static, cyclic sequences in which the amplitude of the demand is gradually increased during the test. However, for many structural materials and components, the loading history can have a significant effect on the resulting nonlinear response. This issue is well-documented in FEMA P-440A, *Effects of Strength and Stiffness Degradation on Seismic Response* (FEMA, 2009a) as illustrated in bridge pier tests performed by Takemura and Kawashima (1997). These tests are described in FEMA P-440A, and an excerpt is shown in Figure 3-5. The figure shows that the number of cycles used in the loading protocol, the amplitude of each cycle, and the sequence of the loading cycles can result in significantly different hysteretic response in terms of the level of degradation and how quickly it occurs.

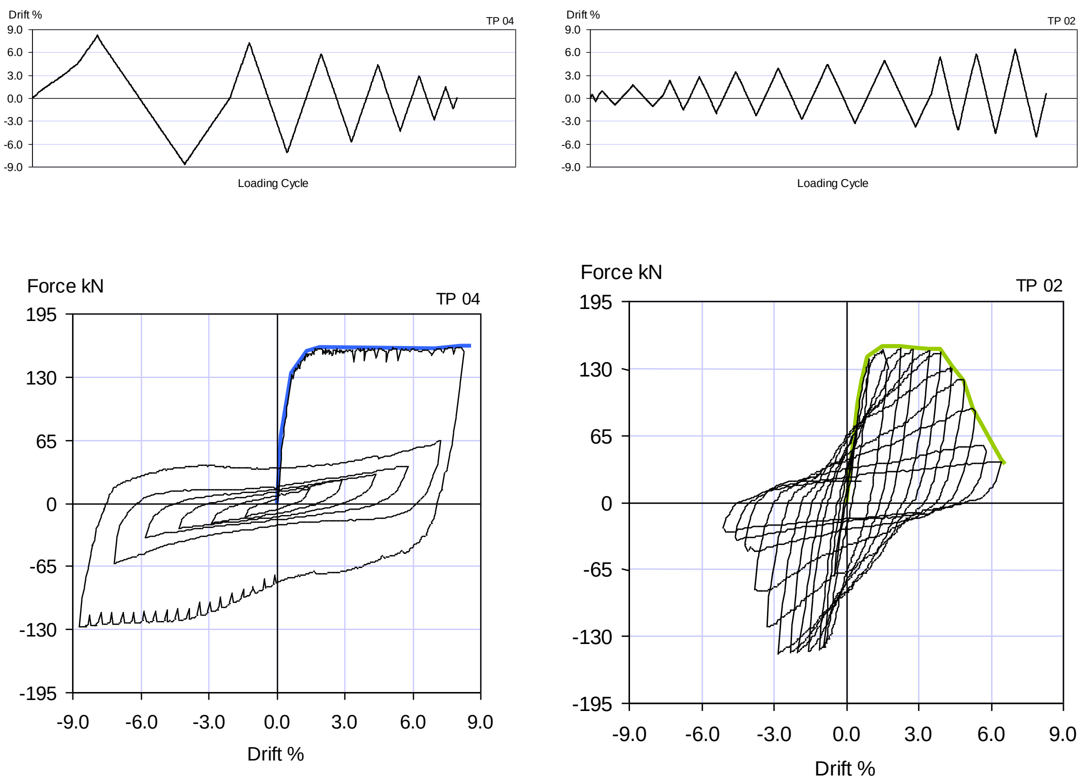

Figure 3-5 Different hysteretic responses for identical reinforced concrete bridge piers subjected to different cyclic loading protocols (FEMA, 2009a).

Cyclic loading protocols should be designed to capture these effects for various structural components and systems. Also, a portion of laboratory tests intended for validation should employ protocols that are representative of real earthquake loading, which is broadband in nature. Research Initiative 3.5a is intended to address these issues by developing guidelines for loading protocols that are specifically targeted for development and validation of nonlinear analysis models.

3.5.2 Best Practices for Future Benchmark Testing

The objectives of benchmark testing to develop data for validation and calibration are not necessarily the same as those used in traditional seismic research programs. Many benchmark testing programs might be simpler, more fundamental, and smaller in scale than recent seismic testing programs. Development of best practices includes describing how future testing should be planned, conducted, and documented to ensure accessibility of results and to maximize its usefulness for improving simulation codes.

Proposed Research Initiative 3.5a	
Title	Develop Loading Protocols for Laboratory Testing to Advance Nonlinear Analysis
Objectives	Develop guidelines and protocols to promote the development of test data that comprehensively describe nonlinear earthquake response under different loading protocols, characterizing the random nature of real earthquake demands. This information would be used to improve simulation software.
Scope	Task 1: Identify and review previous research on the effects of loading sequence on performance of structural components and sub-assemblages, including cyclic and real earthquake demands. Review previous research, consensus documents, and standards addressing loading protocols for laboratory testing, such as FEMA 461 (FEMA, 2007). Identify the circumstances in which current practices fail to identify behavioral differences of engineering significance (e.g., Takemura and Kawashima, 1997) and identify, by hypothesis if necessary, other types of components where similar differences might be expected to arise. Task 2: Develop a list of component types and demand ranges where performance is likely to be sensitive to the loading protocol, and identify when it is unlikely to be an issue. Identify a small set of different loading protocols that could be used to test the sensitivity of components to loading sequence. Task 3: Propose and perform trial tests of various component types under different loading protocols to examine hypotheses about when and how component response is affected. Task 4: Recommend loading protocols for future tests that would be appropriate for validating nonlinear models. Prepare a guidelines document with these protocols, including recommendations for future testing programs.
Estimated Timeline	60 months (total); Tasks 1 and 2 (18 months) must be conducted first; Task 3 (18 to 24 months) and Task 4 (18 to 24 months) can run concurrently
Team	Task 1, Task 2, and Task 4 should be conducted by a team of 4 to 6 researchers and engineering practitioners; each test series identified under Task 3 should be conducted by a research team (faculty member and graduate student)
Audience	Researchers; engineering practitioners; others conducting experimental testing
Product	Guidelines

In order to be useful for validation and calibration efforts, research must be properly documented and accessible to others. In the past, research results have often been poorly documented. Prior to the advent of the George E. Brown, Jr. Network for Earthquake Engineering Simulation (NEES), there hasn't been a single convenient resource for archival of research information. Since NEES has been in existence, an archival process exists. Research Initiative 3.5b is intended to result in best practices for development and management of test data.

Questions to be considered in developing best practice guidelines include:

- What data would be useful for developing linkages between model output and structural performance characteristics and acceptance criteria, and at what level of detail (e.g., phenomenological, macro-, meso-, and micro-scale) is needed?
- What are the objectives of the tests in relation to analysis software validation and calibration, and what new insights will they provide that are not currently

available from previously performed tests (including tests conducted in the United States and internationally)?

- What is the best form of tests to facilitate their replication by simulation? For example, complex hybrid loading regimes are difficult to reproduce with simulation.
- How can analytical parameter studies of structural systems or components be used to identify experimental specimen design characteristics that will yield the most useful information about system behavior at full scale; and how can these be used to ensure that test results and data will fill relevant gaps in knowledge?
- What documentation protocols would provide the best balance between completeness and accessibility; and what lessons can be learned from the NEES data collection, curating, and management protocols?

Proposed Research Initiative 3.5b	
Title	Identify Best Practices for Testing and Test Data Management for Validation and Calibration of Software
Objectives	Articulate improved procedures to plan and conduct tests and to archive and disseminate test results for the purposes of validation and calibration of simulation software.
Scope	Task 1: Review and make recommendations on factors to be considered in planning and conducting tests whose primary purpose is to provide data for the validation and calibration of simulation software. Task 2: Review current measurement and archival procedures and make recommendations about how to improve them. Task 3: Develop guidelines on best practices for testing, organizational structures, and management plans to vet, archive, and manage data sets to ensure that more consistent standards are adopted.
Estimated Timeline	12 to 24 months
Team	A small group of researchers and engineering practitioners
Audience	NIST program planners; building officials; researchers; engineering practitioners; and selected NEES site managers
Product	Guidelines or report describing consensus archiving approach; website repository

3.5.3 Development of Specific Testing Programs

It is anticipated that the results of previously defined research initiatives will identify well-defined shortcomings in existing simulation tools for which there are insufficient test data currently available to guide the improvement of available models. Research Initiative 3.5c is intended to develop a testing plan for addressing these shortcomings.

Proposed Research Initiative 3.5c	
Title	Develop a Testing Plan to Address Critical Data Needs for Validation and Calibration of Software
Objectives	Identify specific testing programs needed to provide experimental data to validate and calibrate nonlinear simulation software in areas of engineering significance where appropriate data are not currently available.
Scope	Task 1: Review the results of preceding initiatives, and other relevant work, that identifies gaps in currently available test data. Task 2: Develop a consensus-based testing plan that identifies testing needed to fill critical gaps in available data for validation and calibration of simulation codes. These tests should cover important structural components and systems, as identified in Research Initiative 3.4. For any blind prediction exercises included in the plan, utilize the results of Research Initiative 3.1, and anticipate the tiered approach of verification, validation, and calibration to ensure the exercise is most useful.
Estimated Timeline	18 to 24 months
Team	Researchers and engineering practitioners
Audience	NIST program planners; researchers; other funding agencies
Product	Testing plan; white papers or short reports on areas of needed testing

Chapter 4

Modeling Capabilities

This chapter addresses deficiencies in nonlinear dynamic analysis related to inadequate mathematical models for materials and components, gaps in fundamental knowledge about system behavior, and explicit consideration of uncertainty in analysis. Proposed research and development initiatives are categorized into the following two groups:

- **Fundamental Research Initiatives.** Fundamental research initiatives include items for which there is a significant knowledge gap in how to represent a certain physical behavior in analysis, or for which the behavior is generally understood but the existing mathematical models are inadequate. Also included in this area are items related to identification, quantification, and inclusion of uncertainty in the analysis process. Fundamental research initiatives are expected to result in new mathematical models and procedures that would need to be incorporated into existing software and engineering guidelines and standards.
- **Implementation-Oriented Initiatives.** Implementation-oriented initiatives include items for which the underlying theories and analysis methods are generally developed, but there is a lack of understanding in some aspect of analysis or behavior. It is expected that existing software codes can be used to evaluate implementation-oriented initiatives, and one question might be whether or not to attempt to model the effect in the analysis. Implementation-oriented initiatives are expected to result in guidelines, reports, or Technical Briefs clarifying the importance of each issue, and how to best implement the recommended solution in practice.

4.1 Fundamental Research Initiatives

4.1.1 Inherent Damping

Energy dissipation in structures is typically modeled using Rayleigh or modal damping. These methods, originally developed for linear analyses, can be problematic and inaccurate in nonlinear dynamic analyses. Guidance is needed on the best ways to use Rayleigh and modal damping in the near term, and research is needed to develop improved approaches for modeling damping in nonlinear analysis that reflect the true physics of structural response and energy dissipation.

When a structure responds to earthquake shaking, there are several sources of energy dissipation that will influence structural response, and should be included in nonlinear analysis. As the shaking intensifies, the character and sources of energy dissipation change in a number of ways (Jeary, 1986), including:

- Material damping in structural components may increase due to cracking, bond slip, and other damage.
- Damping in nonstructural components will initially be near zero, then will increase, and either remain constant or continue to increase, until, eventually, the coefficient of friction reduces due to wearing of sliding surfaces.
- Damping in the foundation and soil will increase due to nonlinearities in highly stressed regions of soil and radiation damping.
- Yielding in structural steel or reinforcing steel will provide displacement-dependent hysteretic energy dissipation.

For low levels of shaking, the main seismic force-resisting system remains elastic, and energy dissipation occurs through inherent, or natural damping. Inherent damping is related to material damping in the structural components and friction in connections and nonstructural components. Specifically excluded from inherent damping is energy dissipation associated with soil-structure interaction, or any other source outside the building envelope.

The most general form of global viscous damping is Caughey damping, where the damping matrix, C_C, is formed as a combination of the mass, M, and stiffness, K, matrices:

$$C_C = M\sum_{j=0}^{N-1} a_j \left[M^{-1}K \right]^j \tag{4-1}$$

where N is the number of dynamic degrees of freedom, and a_j are constants that are determined to produce the desired damping ratios in the various modes. Caughey damping with all modes included is generally undesirable because of the difficulty of obtaining the coefficients a, and because the resulting damping matrix is fully populated.

The most common utilization of Caughey damping is through Rayleigh damping, where the damping matrix, C_R, retains only the first two terms in equation 4-1:

$$C_R = a_0 M + a_1 K \tag{4-2}$$

In this formulation, all vibration modes will be damped, but the damping ratio can be directly established at only two specified frequencies or modes.

A second common approach is to use modal damping, where the modal damping matrix, C_M, is created as follows:

$$C_M = M\left[\sum_{i=1}^{n}\frac{2\xi_i\omega_i}{M_i}\phi_i\phi_i^T\right]M \quad (4\text{-}3)$$

where ξ_i is the viscous damping ratio in a given mode, and ω_i, M_i, and ϕ_i are the frequency, generalized mass, and mode shape, respectively, in mode *i*. C_M is identical to C_C when the same number of modes and modal damping ratios are included in each.

Caughey damping, Rayleigh damping, and modal damping have the advantage of providing linear viscous damping and maintaining uncoupled modes in the equations of motion for elastic systems. However, advantages for elastic systems are irrelevant in nonlinear analysis, where various forms of nonlinearity are explicitly considered throughout the structure and equations are solved directly without transforming to modal coordinates. The use of Caughey damping methods with nonlinear systems is largely a carryover from linear analysis procedures.

When Rayleigh damping is used, there are widely varying opinions about whether to use mass-proportional damping ($a_1 = 0$), stiffness-proportional damping ($a_0 = 0$), or some combination of the two. These differences of opinion arise due to concerns over whether the amount of damping based on the elastic stiffness should be adjusted as the structure yields (and softens). For example, if initial stiffness-proportional damping is maintained, does damping in the lower modes artificially increase as the system frequency reduces? This question has led to considerable debate about whether the stiffness component, *K*, in Equation 4-2 should represent the initial stiffness, the tangent stiffness, the secant stiffness, or some combination of these. Other concerns include whether or not the terms a_0 and a_1 should remain constant or vary with the change in stiffness, or whether damping associated with structural elements (or components) that yield during the analysis should be included.

Many of the issues listed above have been examined in the literature (e.g., Hall, 2006; Charney, 2008; Zareian and Medina, 2010; Puthanpurayil, et al., 2011; Smyrou, et al., 2011). Hall (2006) suggests using a capped stiffness-proportional damping, and recommends against using mass-proportional damping ($a_1 = 0$). Charney (2008) recommends the use of damping based on the tangent-stiffness with time varying coefficients a_0 and a_1. Zareian and Medina (2010) recommend elimination of stiffness-proportional damping in yielding regions and use of initial stiffness damping in nonyielding regions. Symrou et al. (2011) suggest the use of modal damping with 5% damping in all modes except for the first mode, in which an artificially low damping ratio should be used. Clearly, there is a lack of consensus among researchers as to the best approach for utilizing Rayleigh damping or modal damping in nonlinear analysis.

Commonly used Rayleigh damping and modal damping techniques are not based on the underlying energy dissipation mechanisms in structures:

- Inherent damping is not necessarily velocity-dependent. Measured behavior of buildings under small amplitude motion has clearly shown that inherent damping is amplitude-dependent and frequency-independent.
- Inherent damping is path dependent. As damage accumulates, inherent damping increases, reaches a peak, and then possibly decreases as the frictional sliding surfaces wear.
- Damping is generated in different ways in different components, and evolves differently over time.

The use of Rayleigh or modal damping is, therefore, inconsistent from a theoretical perspective, and should be replaced by more realistic models. However, Rayleigh and modal damping will continue to be used in the near term as fundamental research and development of new model formulations occurs over time. Research initiatives 4.1a and 4.1b are intended to address issue of damping on three fronts:

- Comprehensive study of the current methods for modeling inherent damping in buildings, identification of the limitations of current models, and development of a set of interim recommendations for the best use of current techniques.
- Collection of information on the true nature of inherent damping in structures, which can be done by mining the results of previous experiments (e.g., Network for Earthquake Engineering Simulation Research (NEESR) projects), or by studying information on damping in building structures that has been gathered by the wind engineering community (e.g., Jeary, 1986; Kareem and Gurley, 1996). A program of laboratory and field measurements will be necessary if the existing data are not sufficient.
- Development of improved models that reflect the true nature of damping. As currently envisioned, inherent damping is a local, component-based phenomenon, and should be modeled as such. Additionally, material damping models should follow actual building behavior and be able to evolve in magnitude and character as a structure is damaged. For example, damping in concrete elements might begin as linear viscous (as appropriate for linear analysis), and then evolve into a frictional or hysteretic model as the fraction of energy dissipation due to minor cracking increases, as presented in Bowland and Charney (2010). Other viable models should also be explored, including an alternative approach to modeling inherent damping as a frequency-independent material loss factor. An implementation of this is available in LS-DYNA (LSTC, 2013), where the loss factor is applied to the tangent stiffness.

Proposed Research Initiative 4.1a	
Title	Recommend Best-Practice Approach for Modeling Damping Using Current Methods
Objectives	Review current damping models and develop guidelines for their use.
Scope	Task 1: Perform a literature review of existing analytical modeling approaches for damping. Task 2: Perform analytical studies of realistic archetypical buildings (steel and reinforced concrete systems) to help determine how sensitive analysis results are to alternative damping models and related assumptions. Task 3: Prepare a report with findings and recommendations for how to best use current methods.
Estimated Timeline	Approximately 24 months
Team	One research team (faculty member and graduate student) in collaboration with one or more engineering practitioners.
Audience	Engineering practitioners, researchers; software developers
Product	Short report or Technical Brief

Proposed Research Initiative 4.1b	
Title	Develop New Inherent Damping Methods
Objectives	Develop new approaches to modeling inherent damping that are closely based on the underlying theoretical behavior.
Scope	Task 1: Develop a database of observed damping behavior. This would involve performing a literature review of physical damping in materials, components, and structures. There are many papers on this topic, many coming from the wind engineering arena. This information would be archived in a database of collected information. The team would provide recommendations for laboratory and field measurements to fill gaps in available information. Task 2: Develop new inherent damping models. This would entail developing component-based damping models that have the ability to produce a range of behavior, from viscous, to frictional, to hysteretic, and for which the nature of damping and the magnitude of damping evolve with the response.
Estimated Timeline	Approximately 5 years
Team	Envisioned as a “grand challenge” type project requiring multiple teams of Principal Investigators at multiple universities, several graduate students, and several engineering practitioners.
Audience	Engineering practitioners, researchers; software developers
Product	Report series; database of damping behavior

4.1.2 Parameters for Standard Nonlinear Cyclic Component Models with Degradation

A key challenge in using nonlinear analysis for design is defining modeling parameters for nonlinear component models. Currently, ASCE/SEI 41-06, *Seismic Rehabilitation of Existing Buildings* (ASCE, 2007), is the primary engineering resource for nonlinear modeling parameters and acceptance criteria. The parameters specified in ASCE/SEI 41 are based on a generalized force-deformation relationship for nonlinear components, which was introduced in Chapter 2, and illustrated in Figure 2-2.

Force-displacement relationships in ASCE/SEI 41 are described in terms of deformation limits *a, b,* and *c*, or deformation ratios *d* and *e,* which are defined based on the characteristics of the structural component under consideration (e.g., geometry, strength, reinforcement, and controlling behaviors). Although the provisions of ASCE/SEI 41 have gained widespread use in practice, there are important shortcomings with regard to current nonlinear dynamic analysis needs:

- Because they were primarily intended for use with nonlinear static analysis, generalized force-deformation relationships lack information for defining cyclic loading effects.
- Because they were primarily intended for existing building components, parameters and acceptance criteria described by force-deformation parameters are not necessarily appropriate for performance expectations in new building design.
- Because they are related almost exclusively to generalized hinge or nonlinear spring type models, it is unclear how criteria relate to more detailed fiber or continuum models.
- Criteria do not include consideration of the expected variation (dispersion) in modeling parameters or response prediction.

Research Initiative 4.2 is intended to develop a framework for a structural component model that will extend the generalized force-deformation curves in ASCE/SEI 41 to explicitly consider cyclic loading effects for nonlinear dynamic analysis. The idea is to define an idealized model and descriptive parameters that can be used to extract data from monotonic and cyclic tests in a more consistent manner, calibrate the response of computational models for monotonic and cyclic loading, and develop and implement nonlinear cyclic models for nonlinear dynamic analysis.

Many cyclic hysteretic models exist in the literature, and the intent is not to develop a new model. Rather, the goal is to define key features and parameters of cyclic response that are common to most models. The model parameters should reflect both the central value (median or mean) of response and dispersion in response.

The cyclic model parameters are expected to explicitly recognize the degradation in response that occurs due to cyclic loading. Whereas the current ASCE/SEI 41 parameters are implicitly calibrated to the cyclic envelope curve for loading under a standard cyclic loading protocol, the proposed initiative would differentiate the response as a function of an appropriate cyclic damage or demand index. The cyclic model parameters should be established so they enable the development and calibration of models that differentiate between alternative loading histories and degradation due to in-cycle versus cyclic response.

Proposed Research Initiative 4.2a	
Title	Develop a Generalized Cyclic Component Model
Objectives	Extend the ASCE/SEI 41 generalized component model concept to develop a generalized model framework, and associated parameter definitions, that explicitly account for cyclic loading effects.
Scope	Task 1: Conduct a literature review of existing cyclic component models and their relationship to simulating structural response. Task 2: Develop definitions of generalized cyclic model parameters. Task 3: Develop guidance on calibration of the cyclic model parameters.
Estimated Timeline	Approximately 24 to 36 months
Team	Small team of researchers and engineering practitioners with experience in modeling of structures, supported by one or more graduate students.
Audience	Software developers; researchers; engineering practitioners
Product	Report, including recommendations for implementation (e.g., in ASCE/SEI 41)

Proposed Research Initiative 4.2b	
Title	Calibrate Parameters for a Generalized Cyclic Component Model
Objectives	Using the framework developed in Initiative 4.2a, calibrate parameters for common structural systems (e.g., steel and concrete moment frames, concrete walls, and other systems) using available test data and other evidence.
Scope	Task 1: Identify candidate structural systems for which to develop parameters, based on the prevalence of the systems and the availability of necessary test data that capture the desired range of response. Task 2: Calibrate the cyclic model parameters for selected structural components developed in Research Initiative 4.2a.
Estimated Timeline	24 to 36 months
Team	Researchers and engineering practitioners with experience in modeling of structures, supported by multiple graduate students.
Audience	Software developers; researchers; engineering practitioners
Product	Report, including recommendations for implementation (e.g., in ASCE/SEI 41)

The proposed initiative, divided into two parts, is intended to build on prior research to develop nonlinear cyclic models (Initiative 4.2a) and to calibrate them for design (Initiative 4.2b). For example, cyclic modeling parameters for concentrated plastic hinges of steel and concrete moment frames have been proposed in PEER/ATC-72-1, *Modeling and Acceptance Criteria for Seismic Design and Analysis of Tall Buildings* (ATC, 2010). The proposed initiative would develop generic parameters that could be adapted to alternative hysteretic models, whereas the modeling parameters in PEER/ATC-72-1 were developed for a specific cyclic hysteretic model (Ibarra et al., 2005). The proposed initiative may also offer guidance similar to that described in the *Guidelines for Performance-Based Seismic Design of Tall Buildings* (PEER, 2010) on how to use and interpret the results of models, depending on their ability to capture cyclic or in-cycle degradation over the range of expected loading.

4.1.3 Phenomenological Models with Degrading P-M_y-M_z and P-M-V Interaction

Certain structural components are sensitive to three-dimensional response and the interaction of axial load (P), moment (M), and shear (V). However, nonlinear hysteretic models that accurately capture these interactions are much less developed than uniaxial models. For example, the generalized force-deformation response curves in ASCE/SEI 41 are almost exclusively uniaxial models, except that in some cases, model parameters differentiate certain response modes as a function of other force components (e.g., hinge rotation parameters in concrete beams are specified as a function of the shear force in the member) in recognition of these interaction effects. Although computational models exist for capturing nonlinear interaction of axial load and bending moments (e.g., plasticity-based yield surface or fiber-type models with P-M or P-M_y-M_z interaction), the ability of these models to capture and differentiate between cyclic and in-cycle degradation is not well developed. Moreover, modeling techniques to simulate nonlinear interaction of axial load, moment, and shear (i.e., P-M-V interaction) are limited, and are also not well developed. Strength and stiffness degradation due to these effects can be important for structures that do not conform to capacity design requirements that limit inelastic effects in columns and walls and under large story drifts leading to collapse.

Uniaxial phenomenological hysteretic hinge models (Figure 4-1) have been a mainstay approach in seismic response analysis for many years, and have been developed to the point of capturing cyclic strength and stiffness degradation fairly well. Such models generally employ various rules to control the loading and unloading stiffness, and to differentiate between cyclic and in-cycle degradation and pinching effects. These models have been used in studies examining the collapse capacity of structures (e.g., FEMA, 2009d; NIST, 2010c) and are widely employed in earthquake engineering research. Although such models are able to capture nonlinear cyclic degradation well, it is difficult to extend their rule-based formulations to multi-axial response.

Multi-axial response is significant in beam-columns in moment frames where axial loads vary significantly due to earthquake overturning effects and where biaxial bending is significant (i.e., P-M or P-M_y-M_z interaction). Although plasticity-based yield surface models can simulate yielding under P-M_y-M_z interaction (e.g., El-Tawil and Deierlein, 2001a, 2001b; Hajjar and Gourley, 1997; Hajjar et al., 1997), existing models are limited in their ability to model cyclic degradation and post-peak softening. Inelastic softening can occur in steel beam-columns due to local and torsional-flexural buckling, and in concrete beam-columns due to local buckling and fracture of reinforcing bars. Similar limitations are also true of fiber-hinge models (e.g., Scott and Fenves, 2006), which can capture steel yielding and concrete crushing fairly well, but cannot capture degradation due to local buckling and fracture. Although there has been research to adjust fiber-model material parameters to simulate these localized effects (e.g., Kunnath et al., 2009), or to incorporate cyclic softening in yield-surface hinge models, this research has not yet developed to the point of providing robust and reliable models for practical implementation.

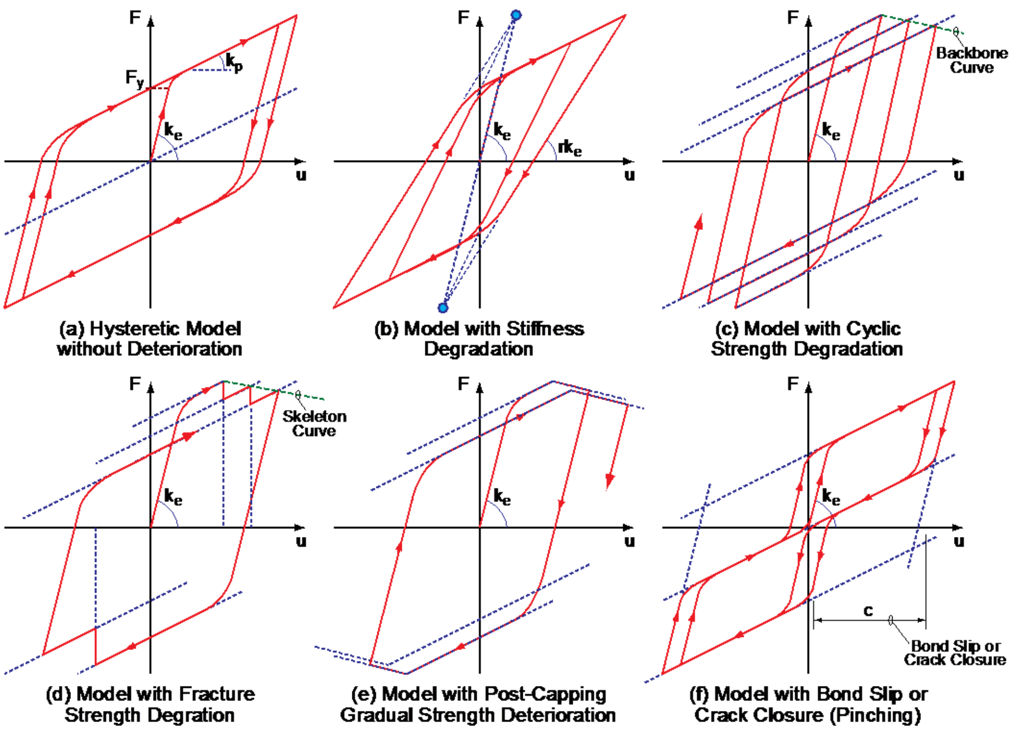

Figure 4-1 Types of uniaxial hysteretic response models (NIST, 2010d).

Another component of nonlinear interaction, which is particularly important for analyzing the response of non-ductile concrete and masonry structures, involves the interaction of axial load, moment, and shear (P-M-V interaction) in beam-columns and walls. The nonlinear interaction of these effects is particularly important for existing buildings that were designed and constructed without capacity design requirements to limit shear failures, because these effects reduce lateral resistance and can lead to loss of vertical load-carrying capacity in columns and walls. Several models have been developed, and, to a limited extent, applied in research (e.g., Elwood and Moehle, 2008; Wallace et al., 2008). However, as in the case of degrading *P-M* hysteretic models, *P-M-V* models have not been sufficiently developed for practical use in assessment and design. Further research is necessary to both improve the theoretical formulations and to calibrate model parameters to engineering design parameters.

Research Initiative 4.3 (divided into three parts) is focused on development, validation and calibration of $P\text{-}M_y\text{-}M_z$ and *P-M-V* interaction models in beam-columns and slender walls.

Proposed Research Initiative 4.3a	
Title	Develop Phenomenological Beam-Column Models with Degrading $P\text{-}M_y\text{-}M_z$ Interaction
Objectives	Develop, implement, validate, and calibrate phenomenological models to simulate cyclic strength and stiffness degradation under the effects of combined axial load and moment ($P\text{-}M_y\text{-}M_z$) in beam-columns. This initiative is intended to focus on phenomenological type modes, rather than more fundamental models, due to the inherent complexity of the local effects. The model formulation is expected to be generally applicable for both concrete and steel members, but the validation and calibration would be separate.
Scope	<u>Task 1</u>: Perform a literature review to better understand $P\text{-}M_y\text{-}M_z$ interaction and review previous research to characterize behavior and develop analytical models. <u>Task 2</u>: Develop a mathematical $P\text{-}M_y\text{-}M_z$ model formulation (or alternative fiber-hinge and limit-surface formulations) that incorporates cyclic and in-cycle strength and stiffness degradation. <u>Task 3</u>: Conduct preliminary validation and calibration of $P\text{-}M_y\text{-}M_z$ model formulation(s) to refine and finalize the model for steel and concrete beam-columns. <u>Task 4</u>: Conduct final validation and calibration of $P\text{-}M_y\text{-}M_z$ model formulation(s) for steel and concrete beam-columns based on available test data and information. <u>Task 5</u>: Conduct studies to explore practical application of the model to inform design practice, and to identify computational issues that may arise through implementation of the model in large, realistic building models. <u>Task 6</u>: Develop guidelines for implementation and use of $P\text{-}M_y\text{-}M_z$ interaction in analysis and design.
Estimated Timeline	Approximately 5 years; Tasks 1, 2, and 3 in years 1 through 3; Task 4 in years 3 through 4; and Tasks 5 and 6 in years 4 through 5
Team	Multiple researchers and engineering practitioners; Tasks 1, 2, and 3 performed by one research team (faculty member and graduate student) in collaboration with one or more engineering practitioners; Tasks 4 and 5 may require two research teams (faculty member and graduate student) in collaboration with engineering practitioners; all team members would collaborate on Task 6
Audience	Software developers; researchers; engineering practitioners
Product	Report, including recommendations for software implementation and codification of appropriate model parameters (e.g., in ASCE/SEI 41)

Proposed Research Initiative 4.3b	
Title	Develop Phenomenological Beam-Column Models with Degrading *P-M-V* Interaction
Objectives	Develop, implement, validate, and calibrate phenomenological models to simulate cyclic strength and stiffness degradation under the effects of combined axial load, moment, and shear (*P-M-V*) in beam-columns. This initiative is intended to focus on phenomenological type modes, rather than more fundamental models, due to the inherent complexity of the interaction of effects. The model formulation is expected to be generally applicable, but the validation and calibration would emphasize *P-M-V* interaction in concrete beam-columns, which are often encountered in design practice.
Scope	<u>Task 1</u>: Perform a literature review to better understand *P-M-V* interaction and review previous research on testing of beam-columns to develop analytical models. <u>Task 2</u>: Develop a mathematical *P-M-V* model formulation (or alternative fiber hinge and limit-surface formulations) that incorporates cyclic and in-cycle strength and stiffness degradation. <u>Task 3</u>: Conduct preliminary validation and calibration of *P-M-V* model formulation(s) for concrete beam-columns to refine and finalize the model. <u>Task 4</u>: Conduct final validation and calibration of *P-M-V* model formulation(s) for concrete beam-columns based on available test data and information. <u>Task 5</u>: Conduct studies to explore practical application of the model to inform design practice and to identify computational issues that may arise through implementation of the model in large, realistic building models. <u>Task 6</u>: Develop guidelines for implementation and use of *P-M-V* interaction in analysis and design.
Estimated Timeline	Approximately 5 years; Tasks 1, 2, and 3 in years 1 through 3; Task 4 in year 3; and Tasks 5 and 6 in years 3 through 5
Team	Tasks 1, 2, 3, 4, and 5 performed by one research team (faculty member and graduate student), overseen by a group of researchers and engineering practitioners; some team members may overlap with Research Initiatives 4.3a and 4.3c; all team members would collaborate on Task 6
Audience	Software developers; researchers; engineering practitioners
Product	Report, including recommendations for software implementation and codification of appropriate model parameters (e.g., in ASCE/SEI 41)

Proposed Research Initiative 4.3c	
Title	Develop Phenomenological Slender Wall Models with Degrading *P-M-V* Interaction
Objectives	Develop, implement, validate, and calibrate phenomenological models to simulate cyclic strength and stiffness degradation under the effects of combined axial load, bending and shear (*P-M-V*) in slender (flexural dominant) walls. The initiative is intended to focus on phenomenological type modes, rather than more fundamental models, due to the inherent complexity of the interaction of effects. The model formulation is expected to be generally applicable, but the validation and calibration would emphasize *P-M-V* interaction in concrete and masonry walls, which are often encountered in design practice. This initiative is intended to be informed by Research Initiative 4.3b.
Scope	<u>Task 1</u>: Perform a literature review to better understand *P-M-V* interaction and review previous research on testing of slender walls to develop analytical models. <u>Task 2</u>: Develop a mathematical *P-M-V* model formulation that incorporates cyclic and in-cycle strength and stiffness degradation. It is anticipated that this would be a fiber-type implementation that is an extension of fiber implementations that are currently used for *P-M* interaction. <u>Task 3</u>: Conduct preliminary validation and calibration of *P-M-V* model formulation(s) for concrete and masonry walls to refine and finalize the model. <u>Task 4</u>: Conduct final validation and calibration of *P-M-V* model formulation(s) for concrete and masonry walls based on available test data and information. <u>Task 5</u>: Conduct studies to explore practical application of the model to inform design practice and to identify computational issues that may arise through implementation of the model in large, realistic building models. <u>Task 6</u>: Develop guidelines for implementation and use of *P-M-V* interaction in analysis and design.
Estimated Timeline	Approximately 5 years; Tasks 1, 2, and 3 in years 1 through 3; Task 4 in year 3; and Tasks 5 and 6 in years 3 through 5
Team	Tasks 1, 2, 3, 4, and 5 performed by one research team (faculty member and graduate student), overseen by a group of researchers and engineering practitioners; some team members may overlap with Research Initiatives 4.3a and 4.3b; all team members would collaborate on Task 6
Audience	Software developers; researchers; engineering practitioners
Product	Report, including recommendations for software implementation and codification of appropriate model parameters (e.g., in ASCE/SEI 41)

It will be a significant research effort to develop robust models to simulate P-M_y-M_z and *P-M-V* response. It is anticipated that the research would explore alternative phenomenological formulations, including both interaction limit state surface models (i.e., yield surface models) and fiber-hinge type models. Model development should make use of available test data to formulate the model and calibrate model parameters, although additional testing and detailed modeling may be required for some issues. Theoretical formulations should be amenable to implementation in nonlinear analysis software, where the calculations of stiffness and state determination are self-contained within the element; however, global solution algorithms may need improvement to track highly degrading response. Validation and calibration of models for concrete and steel beam-columns and concrete walls may relate to NIST initiatives funded under other programs (e.g., NIST, 2010e; NIST, 2011a).

4.1.4 Improved Models of Isolators, Dampers, and Other Response Modification Devices

Passive energy dissipation and seismic isolation devices are characterized by non-linear force-deformation characteristics and hystereses. Structures incorporating passive energy dissipation or seismic isolation defer most of the energy dissipation in the system to these devices, resulting in reduced forces or deformations, and reduced levels of damage to the structure itself. They are generally designed to achieve energy dissipation without substantial damage or deterioration. Alternatively, they can be designed as sacrificial components that are easily replaced. Energy dissipation and seismic isolation technologies can be an attractive solution where enhanced performance is a major objective, especially in cases where protection of non-structural components and contents is important.

There are three basic types of systems where energy dissipation or isolation devices are used:

- **Systems with auxiliary energy dissipation devices (only).** Devices such as viscous fluid dampers, viscoelastic dampers, friction devices, and metallic yielding devices, which are often proprietary, are incorporated into the superstructure to dissipate seismic energy in lieu of (or in addition to) the primary seismic force-resisting system. For structures in regions of high seismicity, it is usually not possible to dissipate all of the seismic energy in these devices, so some inelastic deformation still occurs in the primary structural components. Viscous and viscoelastic devices are primarily velocity dependent, while frictional and metallic yielding devices are generally displacement dependent. In most cases, the force-velocity or force-displacement behavior of the devices is highly nonlinear, but is not difficult to model mathematically because the hystereses are stable, and (except for temperature effects) do not degrade in force or stiffness over repeated cycles.
- **Systems with seismic isolation devices (only).** Devices such as such as rubber isolators (with or without lead cores) and friction-pendulums are incorporated at the base of a structure. The primary goal of these devices is to modify the vibrational characteristics of the structure such that most of the lateral deformation occurs at the isolation plane. Most isolation devices operate in a biaxial manner, and dissipate energy through viscoelasticity, metallic yielding, or sliding friction. In buildings with isolation devices, the superstructure is expected to remain elastic (or nearly elastic) during strong earthquake shaking.

- **Systems with both seismic isolation and auxiliary energy dissipation devices.** Systems in which energy dissipation devices are utilized in the isolation plane as part of the isolation system. The purpose of adding energy dissipation is to reduce the deformations that will occur at the isolation plane.

Numerical models for energy dissipation and isolation devices have been well developed by manufacturers and researchers, which has allowed for extensive and successful implementation in buildings and non-building structures. In the majority of cases, energy dissipation and seismic isolation devices can be characterized as bilinear, multi-linear, or smooth-variable force-displacement curves that can be incorporated into analytical models. For viscous and viscoelastic energy dissipation devices, exponential coefficients are used to shape the hysteresis loops to match those observed in testing. More complex models based on thermodynamics using integro-differential equations are often simplified through the use of multilinear response curves to match existing software for practical purposes, while treating many of the behavioral aspects as parameter variability.

One of the key issues regarding analytical modeling of energy dissipation and isolation devices relates to the inherent (or perceived) variability in the material properties, manufacturing processes, and tolerances. Although improvements in these areas continue to be made, and properties are becoming more consistent and predictable, U.S. codes and standards require the analysis of structures utilizing these technologies to incorporate potential variability on the order of 10%, and both prototype and production components must be verified through testing, which is also specified in the code.

In addition to variability in material properties and manufacturing processes, the following concerns related to modeling of energy dissipation and isolation devices exist:

- Viscous fluid and viscoelastic devices have force-displacement properties that are dependent on both frequency of excitation and operational temperature (Constantinou et al., 1998; Hanson and Soong, 2001). A limited review of commercial software available for modeling such devices (e.g., SAP2000, PERFORM 3D) indicates that these characteristics are not modeled directly. It is possible to handle frequency dependence by the use of Maxwell-type models, which consist of assemblages of springs and dashpots (Singh et al., 2003). Currently, temperature dependence cannot be modeled. Although this may not be important for devices used in seismic applications where the loading duration is measured in seconds, it can be a significant issue in wind applications, where loading can occur over several minutes, or even hours.
- Little consideration is given in the literature on effective damping that may be lost due to deformations in the linkage system connecting the devices to the

structure, and within the structure itself. For example, modeling diaphragms as rigid may result in excessive estimates of added damping effectiveness if there is significant in-plane deformation that actually occurs in the diaphragm. More serious losses in effective damping can occur in certain configurations, such as toggle brace systems, where the axial forces in the linkage are significantly amplified (Charney and McNamara, 2008).

- The relative effectiveness of added damping can also be reduced significantly if the superstructure yields during the earthquake.
- For analysis to evaluate structural collapse, it is necessary to consider failures that may occur in energy dissipation and isolation devices due to excessive travel, loss of seal pressure, or other mechanical difficulties. An example of such concerns for steel moment frames with viscous fluid damping devices is provided in Miyamoto et al. (2011).

Research Initiative 4.4 is intended to examine and address issues related to modeling of energy dissipation and isolation devices. It is related to Research Initiative 4.1, which specifically focuses on damping.

Proposed Research Initiative 4.4	
Title	Improve Modeling of Seismic Isolators, Energy Dissipation Devices, and Systems
Objectives	Improve the state of the practice of modeling structures that incorporate seismic isolation systems, auxiliary passive energy systems, or combinations of such systems.
Scope	Task 1: Develop a comprehensive catalog of the types of isolator and energy dissipation devices that have been used in the past, or will be available for use in the immediate future. Task 2: Review the modeling approaches recommended by device manufacturers or research institutions, and correlate this with the need for capturing relevant behaviors. Task 3: Review modeling approaches used in currently available software, and correlate this with the need for capturing relevant behaviors. Task 4: Investigate potential pitfalls associated with modeling, particularly as they relate to interaction with connections, linkages, and the supporting superstructure. Task 5: Provide written guidance for modeling seismic isolator systems, passive energy devices, their connecting elements, and the superstructure.
Estimated Timeline	Approximately 3 Years
Team	Research team (faculty member and one or more graduate students), overseen by a group of researchers, engineering practitioners, and industry representatives.
Audience	Engineering practitioners; software developers; researchers
Product	Short report or Technical Brief

4.1.5 Characterization and Inclusion of Uncertainties in Nonlinear Response Simulation

As discussed in NEHRP Technical Brief No. 4, *Nonlinear Structural Analysis for Seismic Design, A Guide for Practicing Engineers* (NIST, 2010d), variability in response prediction can generally be attributed to three main sources: (1) hazard uncertainty in the ground motion intensity; (2) ground motion uncertainty arising from frequency content, duration, and other characteristics of ground motions of a given intensity; and (3) structural behavior and modeling uncertainties. The third source, structural behavior and modeling uncertainties, can arise from variability in physical attributes of the structure (e.g., material properties, geometry, structural details), variability in the nonlinear behavior of the structural components and system, and variability in the mathematical representation of the actual behavior. These are further described as follows:

- **Uncertainties in Physical Attributes.** Physical attributes of a building pertain to the materials and the geometric description of the components. For example, in a concrete structure, material properties include those of the concrete and steel reinforcement, and geometry includes member dimensions and the placement and detailing of reinforcing bars. Material and geometry are often abstracted through the definition of normative parameters, such as nominal material properties or reinforcing bar sizes and deformations. However, variations in the normative properties (e.g., the measured compressive strength of a concrete cylinder or the area of a reinforcing bar) represent only one part of the actual variability, which can include variations in the strength of concrete throughout the structure or in the reinforcing bar fabrication tolerances. Thus, variability that is not reflected in nominal material and geometric properties is reflected in variability in the observed nonlinear behavior.
- **Uncertainties in Nonlinear Behavior.** Variability in nonlinear behavior arises due to: (1) variation in physical parameters that are not fully captured by the nominal material and geometric properties (e.g., variability in observed behavior of two "nominally identical" specimens); and (2) variation in response (as compared to current knowledge or observed response) based on limitations in available theory or models. For example, even with extensive calibration to multiple test specimens, empirical models for strength and deformation characteristics of structural components usually exhibit significant scatter in predicted response due to aspects of behavior that are not fully captured by the models. Another source of variability in nonlinear behavior arises due to the load-dependent nature of cyclic response, where models that are validated and calibrated against one type of loading protocol may not be as accurate under alternative loading histories. Therefore, even when the physical parameters are

accurately known, there is still inherent uncertainty in how accurately response can be predicted using these parameters.

- **Uncertainties in the Mathematical Model.** Variability introduced due to differences in the numerical models used to calculate response. These include fundamental differences in the model, such as the variability that is observed between fiber and hinge type models. They can also include more subtle differences that arise due to numerical integration schemes, selection of shape functions, mesh refinement, or damping assumptions.

When nonlinear dynamic analysis is used in the context of ASCE/SEI 41 or Chapter 16 of ASCE/SEI 7-10, *Minimum Design Loads for Buildings and Other Structures* (ASCE, 2010), uncertainty is usually not explicitly included in the analysis itself. It is included in the acceptance criteria (in an ad-hoc manner) through the choice of a design hazard level, statistics on the calculated demands (e.g., mean, median or maximum response quantities), and subjective judgment regarding the acceptable level of certain demand quantities (e.g., limiting deformations, strains, or forces). For example, tall building analysis and design guidelines (e.g., PEER, 2010; LATBSDC, 2011) include requirements to multiply mean response quantities by factors to account for expected variability in response. The collapse assessment methodology outlined in FEMA P-695, *Quantification of Building Seismic Performance Factors* (FEMA, 2009d) considers uncertainty through the use of assumed values of dispersion that are based on judgment as to the quality of the design and analysis efforts. Although the FEMA P-695 procedures were informed by some research on modeling uncertainties, the judgment used in establishing the assumed dispersions was subjective, and somewhat arbitrary.

The procedures used to account for uncertainty in ASCE/SEI 7 and FEMA P-695 do not evaluate uncertainty explicitly because not all of the important uncertainties have been identified and quantified, and a systematic methodology for incorporating uncertainty has not been developed. Several research initiatives in this chapter are closely related to uncertainty. Initiatives that involve uncertainties in mathematical modeling procedures include modeling inherent damping, modeling geometric stiffness (linearized versus consistent stiffness, small versus large displacement analysis), and differences between fiber-type versus hinge-type elements (meso-scale versus macro-scale). Questions related to system torsion (Initiatives 4.8a and 4.8b) arise due to uncertainties in the inertial mass, the strength and stiffness of components in the lateral system, and nonlinear component and system response.

It is recommended that research related to uncertainty move forward on the following four fronts:

1. Identification and quantification of uncertainties in the physical and nonlinear response parameters of materials and components.

2. Identification of and minimization (or elimination) of uncertainties associated with mathematical models. For example, uncertainty associated with choices made in Rayleigh proportional damping can be reduced by developing more rational approaches.
3. Assessment of the influence of uncertainties on computed nonlinear dynamic response. Approaches used in recent research include variation and interpretation of model parameters using Monte Carlo simulation, Latin hypercube sampling, or response surface simulation methods (e.g., Dolsek, 2009; Liel et al., 2009).
4. Development of methodologies for automatically and efficiently incorporating uncertainty in nonlinear analysis and design.

Research Initiative 4.5 (divided into two parts) is considered to be a "grand challenge" type project, and full realization of the four goals identified above could take a decade or more. In the short term, however, significant progress could be made on the first three items to help inform practical procedures to account for modeling uncertainties in design using nonlinear analysis. Success in implementing the fourth item will depend on the development of efficient methodologies for incorporating uncertainty, and on enhancements in modeling and computational efficiency.

Proposed Research Initiative 4.5a	
Title	Characterize Uncertainties in Nonlinear Response Simulation
Objectives	Quantify modeling uncertainties for nonlinear analysis, based on prior published research, to be used as a starting point for follow-on work in Research Initiative 4.5b.
Scope	Task 1: Perform a literature review on previous studies that have investigated the role of uncertainties in nonlinear response of structures. Task 2: Identify the sources and influence of uncertainties in structural material and component model parameters on nonlinear response. Task 3: Identify the sources and influence of uncertainties introduced by the mathematical model formulation on response, and provide recommendations for improved models to reduce these uncertainties.
Estimated Timeline	Approximately 24 months
Team	Research team (faculty members and one or more graduate students)
Audience	Researchers
Product	Report

Proposed Research Initiative 4.5b	
Title	Incorporate Uncertainties into Nonlinear Response Simulation
Objectives	Develop improved procedures to rigorously account for and reduce modeling uncertainties in nonlinear analysis and design.
Scope	Task 1: Develop preliminary analysis procedures and guidelines to account for modeling uncertainties in nonlinear analysis and design. Identify limitations and barriers associated with successful implementation of the procedure. Task 2: Develop statistically robust methods and computational procedures to quantify the effects of uncertainties in nonlinear analysis. Identify the barriers associated with successful implementation of the procedures. Task 3: Provide practical recommendations for including uncertainties in nonlinear analysis, including discussion of a range of procedures amenable to implementation in the short term and longer term.
Estimated Timeline	Approximately 5 years
Team	Envisioned as a "grand challenge" type project requiring multiple teams of Principal Investigators at multiple universities, several graduate students, and several engineering practitioners
Audience	Engineering practitioners; software developers; researchers
Product	Report covering the results of Tasks 1 and 2; short report or Technical Brief summarizing the results of Task 3

4.2 Implementation-Oriented Initiatives

4.2.1 Geometric Nonlinearities

The response of structures due to earthquake shaking can be highly nonlinear due to inelastic behavior of material and changes in geometry, referred to as *geometric nonlinearities*. The effect of geometric nonlinearities on the response of structures can range from negligible to extreme, where in the extreme case, the geometric nonlinearity can result in significant ratcheting (i.e., accumulation of inelastic deformation in one direction), dynamic instability, and collapse of the structure. There are a number of questions regarding how geometric nonlinearities should be implemented in nonlinear dynamic analysis. In this discussion, geometric nonlinear effects are limited to large displacements, rather than large strains, which are defined at the material level rather than the component level.

In concept, geometric nonlinear analysis implies that equilibrium is satisfied on the deformed geometry, although the degree to which this is rigorously achieved varies depending on the analysis formulation. A key assumption relates to approximations used in modeling the kinematics, which determines the accuracy with which large displacements and rotations are modeled in formulating the tangent stiffness and recovering internal member forces. These approximations may involve, for example, small angle assumptions where trigonometric functions are linearized to simplify the calculations (e.g., cos $\theta = 1$; and sin $\theta = \theta$), and whether or not nodal coordinates are updated during the analysis.

Another aspect of geometric nonlinearity relates to the use of geometric stiffness (or stress) matrices to improve the accuracy of the effective stiffness of members (and the structure) to account for the influence of stress resultants (i.e., forces and moments) in a step-wise incremental or iterative analysis. In seismic analyses of buildings, the existing gravity load (and associated axial load, P) along with the displacement of the structure (Δ), typically have a dominant effect on the geometric stiffness. For frame models of buildings, this leads to differences between "P-Delta" (P-Δ) analyses, considered accurate for small but finite displacements, versus large displacement analyses, which are considered to be more accurate. In frame members that experience flexure, further distinctions are made between P-Δ effects (related to displacements between joints) and P-δ effects (related to local member deformations), depending on whether local member deformations are considered in calculating the member tangent stiffness or recovering internal member forces.

As an example of the types of approximations that are encountered, OpenSEES includes the effects of geometric nonlinearity through the use of a variety of special geometric transformations (Denavit and Hajjar, 2013). Three options that are available include: (1) a *linear* transformation, in which geometric nonlinear effects are ignored; (2) a P-Δ transformation, in which small (but finite) displacements and rotations are captured; and (3) a *co-rotational* transformation, in which large displacements are captured. Although the co-rotational transformation is theoretically more accurate, its use tends to make the analysis more sensitive to convergence problems. As a result, P-Δ transformation tends to be the most commonly used method in nonlinear analysis of buildings with calculated story drift ratios less than 3%. Although the theoretical basis for modeling geometric nonlinearities is fairly well understood, consistent best practices for implementation have yet to be established. Ongoing issues related to modeling of geometric nonlinearities include:

- In frame elements, geometric stiffness is a function of the internal forces in the element (primarily axial force, P) and the assumed shape of the element between nodes. If the deformed shape of the element is taken as a straight line, geometric stiffness accounts for *large P-Δ effects*, where Δ refers to the difference in transverse displacement at each end of the element. If the deformed shape of the element is taken as a cubic polynomial, then the geometric stiffness is referred to as *consistent* because the same cubic shape formulation is used to form the elastic stiffness of the element. Consistent geometric stiffness includes large P-Δ effects, as well as *small P-δ effects*, where δ refers to the deviation between the elastic curve and a straight line drawn between the ends of the element. There is general consensus that P-δ effects are usually not important in seismic analysis of buildings, although this depends on the slenderness of the members and extent of distributed yielding (e.g., White and Hajjar, 1991; Adam and Krawinkler, 2004). It is also believed that inclusion of large displacement effects is not necessary if story drifts are less than about 10% of the story height (e.g., Adam and Krawinkler, 2004). There are differences of opinion as to the most appropriate way to include P-Δ effects in an analysis. For three-dimensional analyses, it is important to capture translational and torsional P-Δ effects (Mansuri, 2009), and this can be accomplished through the use of linearized geometric stiffness on an element-by-element basis. Since most commercial and research programs use some form of geometric stiffness, there is some question as to the accuracy of currently employed methods. For two-dimensional analyses, it is often necessary to add a fictitious P-Δ column to capture the destabilizing effects of gravity loads that are not tributary to the modeled elements of the seismic force-resisting system. When a three-dimensional analysis is performed on an assemblage of planar frames, the P-Δ column must capture second order effects in translation for both principal directions, as well as in torsion about the vertical axis. Best practices for capturing torsional P-Δ effects in such systems have not been established.

- Important consequences of geometric nonlinearity include residual deformations and dynamic instability due to ratcheting. Although the tendency of ratcheting can be captured using current nonlinear analysis methods, the magnitude of ratcheting, and the level of ground motion that causes dynamic instability due to ratcheting, are highly sensitive to modeling assumptions and computational procedures (in addition to the characteristics of the input ground motion). Although it might seem possible to avoid this sensitivity by placing limits on calculated residual deformations in a design situation, there is a reluctance to do so because the calculation of residual deformations is highly uncertain. Moreover, if an analysis is intended for evaluation (i.e., to assess the onset of collapse), then large drifts and ratcheting behavior must be captured.
- In the case of large structural systems with slender elements, and for analyses intending to assess collapse capacity, P-δ effects and large displacement effects may need to be considered. White and Hajjar (1991) indicate that errors in fixed-end forces are significantly larger than errors in stiffness formulation when P-δ effects are ignored. This can affect the sequence of hinging in analysis of members with heavy gravity loads.
- The use of consistent geometric stiffness can be problematic for inelastic elements because of discrepancies in the elastic and inelastic deflected shape. This may not be critical for elements modeled directly with phenomenological hinges, but it is likely to be a concern for elements modeled with distributed plasticity (i.e., fiber elements). Assessment of the need to include P-δ effects

would require improved, consistent geometric formulations, or the use of linearized geometric stiffness with refined discretization, where single elements are subdivided into two, three, or four elements along their length.

- Most commercial and research software utilize implicit equation solvers for nonlinear dynamic analysis (e.g., Gauss elimination or other similar methods to solve simultaneous stiffness equations for displacements in each step of the linearized time integration steps). There is reason to believe that explicit analysis solvers might be more suitable, particularly as the structure approaches collapse. The accuracy in assessing the onset of collapse in small displacement analyses (including geometric stiffness) has not been systematically evaluated.

Research Initiative 4.6 (divided into two parts) is intended to clarify the role of geometric nonlinearity in the seismic response of structures, and to develop guidance for best practices. Initiative 4.6a is intended to identify the issues and plan analytical studies. Initiative 4.6a is intended to complete analytical studies and develop guidance on implementation.

Proposed Research Initiative 4.6a	
Title	Evaluate Current Approaches for Modeling Geometric Nonlinearities
Objectives	• Determine if it is necessary to include *P*-Δ effects in structural analysis, and if so, those circumstances and systems for which such effects are most critical. • Determine if it is necessary to include large displacement effects (updating of nodal coordinates) in structural analysis, and if so, those circumstances and systems for which such effects are most critical.
Scope	<u>Task 1</u>: Conduct a literature review on issues related to geometric nonlinearity. <u>Task 2</u>: Evaluate existing computational approaches for including forms of geometric nonlinearity in analysis up to collapse. Specifically address the following issues: (a) geometric stiffness verus state determination; (b) formulation and use of consistent geometric stiffness; (c) implicit versus explicit dynamic analysis; and (d) reliability in predicting dynamic instability. Identify appropriate software (or updates to existing software) as necessary. Finalize analytical procedures for subsequent analysis.
Estimated Timeline	Approximately 12 months
Team	One research team (faculty member and one or more graduate students) in collaboration with an engineering practitioner
Audience	Researchers; software developers; engineering practitioners
Product	Report

Proposed Research Initiative 4.6b	
Title	Develop Guidelines on Modeling Geometric Nonlinearities
Objectives	Complete the analytical studies of Research Initiative 4.6a, determine when it is necessary to include *P*-Δ effects and large displacement effects in analysis, and identify those circumstances and systems for which such effects are most critical.
Scope	Task 1: Design and analyze archetypical buildings that are expected to be sensitive to geometric nonlinearities, and summarize basic findings. Task 2: Provide recommendations for best practices when including geometric nonlinearities in analysis.
Estimated Timeline	Approximately 24 months
Team	One research team (faculty member and one or more graduate students) in collaboration with an engineering practitioner
Audience	Software developers; engineering practitioners
Product	Guidelines

4.2.2 Calibrating and Interpreting Fiber Models for Beam-Columns and Slender Walls

Meso-scale fiber models have the appeal of representing member behavior at a more fundamental level than concentrated hinge type models. However, although fiber models are generally perceived to be more accurate than hinge models, their accuracy depends on the specific circumstances in which the models are applied. Moreover, the use of fiber models in design presents several practical challenges.

Advantages of fiber-type models include: (1) their versatility to model arbitrary cross section geometries made up of different materials; (2) their ability to track gradual inelasticity (e.g., steel yielding and concrete cracking) over the cross section and along the member length; and (3) the separation of abstractions of the hysteretic material response from the member model. Limitations of fiber-type models in simulating highly nonlinear response include:

- Fiber models generally invoke the assumption that plane sections remain plane, which is not necessarily true, particularly at larger deformations and strains. For example, this assumption is inconsistent with the modeling of bond slip or the presence of shear cracking in reinforced concrete members. This assumption may also be violated in steel or concrete sections with high shear or torsional stresses that cause warping of the cross section.
- Calculation of curvatures (and stresses and strains) along the member length can be sensitive to the specified hardening (or softening) modulus of the materials, the assumed displacement (or force) interpolation functions along the member length, and the type of numerical integration and discretization of integration points along the member, which can lead to large errors and inconsistencies in

the curvature and strain demands calculated in the analysis, along with the associated stress resultants (i.e., forces) and member stiffnesses.

- Although curvature assumptions that underlie fiber models make them well-suited for capturing material yielding and strain hardening, they are not suited for capturing softening and degradation associated with large deformations. This includes degradation due to buckling and fracture of steel plates or reinforcing bars, crushing and spalling of concrete, and bond slip of reinforcing bars. Although there have been attempts to incorporate these effects, methods typically employ empirical assumptions that suffer from the same limitations as empirical hinge models. Moreover, the phenomenological calibration to create a softening fiber model tends to result in increased sensitivity to the specified hardening (or softening) modulus, the assumed displacement (or force) interpolation functions, and the type of numerical integration, as they are used the calculation of curvatures along the member length (as noted above).

The advantages of fiber models, however, can outweigh the disadvantages. Because fiber models have been widely used, reported in the literature, and implemented in nonlinear analysis software, their utility cannot be discounted. There is an important need to develop well-substantiated guidance on the implementation, calibration, and use of fiber models for beam-columns, slender walls, and other common applications (e.g., modeling of buckling braces).

Research Initiative 4.7 is intended to improve the state-of-the-practice regarding the use of fiber models through studies addressing: (1) assumptions and procedures for discretizing members over their cross section and along their length; (2) definition of appropriate material parameters to capture cross section distortions, bond slip, and other forms of softening and degradation that influence member response but are not reflected in classical fiber element assumptions; and (3) limitations on the accuracy and use of fiber models. With regard to discretization along the member length, one promising approach for seismic design (with steep moment gradients along the member) is the so-called fiber-hinge type model, in which the specification of the fiber hinge length is coordinated with the definition of effective material parameters. It is envisioned that Research Initiative 4.7 will include thorough review and consideration of available research on fiber element formulations and test data to validate proposed modeling recommendations.

Proposed Research Initiative 4.7	
Title	Calibrate and Interpret Fiber Models for Beam-Columns and Slender Walls
Objectives	Improve the state-of-the-practice for modeling beam-columns and slender walls with fiber models through development of guidance that is validated by comparisons to test data and other well-established models.
Scope	Task 1: Review available research and relevant literature on fiber hinge formulations, their implementation in analysis software, and important behavioral effects in beam-columns, slender shear walls, and other common applications. Task 2: Identify approaches for addressing challenges in establishing cross section discretization, member length discretization, and specification of appropriate material properties. Task 3: Identify available software and evaluate the ability of each to conduct comparative analyses of alternative fiber element implementations. Although it is anticipated that most alternatives will be available in existing software, this may require some limited software coding and implementation (presumably in OpenSees). Task 4: Conduct analyses of comparative fiber implementations and validate through comparisons with test data and other validated models. Develop calibration parameters (e.g., assumed hinge lengths, material properties) for promising modeling methods. Task 5: Evaluate relationships between fiber models and acceptance criteria in ASCE/SEI 41 and other relevant engineering resource documents. Task 6: Develop guidelines and recommendations for use of fiber models in nonlinear analysis and design.
Estimated Timeline	Approximately 3 years
Team	One or more research teams (faculty members and graduate students), overseen by a group of researchers and engineering practitioners
Audience	Software developers; researchers; engineering practitioners
Product	Report documenting results; possible Technical Brief summary of recommendations

4.2.3 Criteria for Modeling Accidental Torsional Effects in Buildings

The PEER *Guidelines* do not require accidental torsion to be considered in serviceability analyses, and do not mention accidental torsion when analyzing systems under maximum considered earthquake shaking. Similarly, modeling of system level accidental torsion is not mentioned in PEER/ATC-72-1, which is one of the primary resource documents for the PEER *Guidelines*. Commentary Section 7.5.3 of the PEER *Guidelines* states that accidental torsion need not be considered for serviceability because, "the torsional eccentricity associated with random variability in loading and material properties will tend towards a mean of zero when considered over many stories and floor levels." Although this observation is not unreasonable, there is no mention of any studies to substantiate it.

Consideration of accidental torsion is currently required in ASCE/SEI 7, which is intended to account for uncertainties in locating the center of mass and the elastic center of rigidity. ASCE/SEI 7 requires that accidental torsion be considered for all rigid and semi-rigid diaphragm buildings, and that accidental torsion be amplified by as much as a factor of three when inherent torsional irregularities are encountered (unless variations in the center of mass to produce 5% accidental eccentricity are explicitly included in the dynamic analysis). It is important to recognize that designing structures for amplified accidental torsion makes them more torsionally resistant, but does not remove the underlying torsional irregularity. The redundancy factor in ASCE/SEI 7 produces a similar design result. Buildings in which there is a lack of redundancy are designed to be stronger, but the underlying lack of redundancy is not removed.

The influence of torsional irregularity in nonlinear systems can be highly amplified because elements at different locations may yield at different times, inducing large (albeit temporary) torsional eccentricities. Problems with unsymmetrical distribution of yielding can occur even in symmetric systems, so the problem is not limited to systems with torsional irregularities (Mansuri, 2009). Mansuri (2009) also indicates that inelastic torsion is more problematic for taller buildings than it is for shorter buildings, which contradicts the basis for omitting accidental torsion in the PEER *Guidelines*. Tall reinforced concrete core wall buildings are a particular concern because: (1) with all of their lateral resistance located in the central portion of the building, they are less torsionally robust than other buildings; (2) lateral systems in these buildings are inherently nonredundant because only a few walls resist load in each direction; and (3) yielding is generally concentrated near the base of the building.

Issues related to whether accidental torsion should be included in nonlinear analysis are unresolved. In particular, practical methods for defining and modeling accidental torsion need to be developed, and these methods must include uncertainty in the center of mass, stiffness, and strength of the principal seismic force-resisting elements. Additionally, acceptance criteria related to story drift should be reassessed to determine whether it is appropriate to place limits on the magnitude of story drifts associated with building torsion versus lateral drift.

Research Initiative 4.8 (divided into two parts) is intended to resolve issues related to accidental torsion in nonlinear analyses. Part 1 (Initiative 4.8a) is intended to determine when accidental torsion needs to be considered. Part 2 (Initiative 4.8b) is intended to develop guidelines for modeling accidental torsion in nonlinear static and dynamic analyses.

Proposed Research Initiative 4.8a	
Title	Develop Criteria for Modeling and Design for Accidental Torsion Effects in Buildings: Part 1
Objectives	Part 1 is intended to answer the question of when accidental torsion needs to be considered in nonlinear dynamic analysis. Determine, through systematic static and dynamic nonlinear analyses, the role of uncertainty in the distribution of stiffness and strength (and lack of redundancy) on the torsional response and collapse resistance of structures.
Scope	Task 1: Perform a literature review on the influence of accidental torsion in linear and nonlinear response. Investigate the topic from the perspective of static and dynamic loading. Find circumstances under which it is believed that unanticipated torsional response (and lack of redundancy) had a significant influence on the performance of real buildings under real earthquakes. Task 2: Identify parameters that can influence torsional response, and identify and quantify the uncertainties that can occur.
Estimated Timeline	Approximately 24 months
Team	Research team (faculty member and one or more graduate students), overseen by a group of researchers and engineering practitioners
Audience	Researchers; software developers; engineering practitioners
Product	Report summarizing results

Proposed Research Initiative 4.8b	
Title	Develop Criteria for Modeling and Design for Accidental Torsion Effects in Buildings: Part 2
Objectives	Extend the Part 1 study in Research Initiative 4.8a to develop guidelines for modeling accidental torsion in nonlinear static and dynamic analyses.
Scope	Task 1: Develop realistic archetypical buildings that are candidates for further study of torsional response. Task 2: Perform 3-dimensional analysis on a variety of systems to determine how accidental torsion influences the response at serviceability, life-safety, and incipient collapse limit states. Task 3: Provide practical recommendations for modeling torsional effects in the form of a Report or Technical Brief.
Estimated Timeline	Approximately 24 months
Team	One or more research teams (faculty members and graduate students), overseen by a group of researchers and engineering practitioners
Audience	Engineering practitioners; software developers; researchers
Product	Guidelines; possible Technical Brief summary of recommendations

4.2.4 Modeling of Collector and Diaphragm Demands in Nonlinear Dynamic Analysis

Diaphragms and collectors are key elements in seismic force-resisting systems. They often consist of several elements that comprise the complete load path. In composite steel deck diaphragms with concrete fill, for example, this includes the concrete and its reinforcing, shear connectors, chord or collector elements, and steel beam connections to the balance of the seismic force-resisting system. Analogies exist for bare steel deck, wood, and precast concrete diaphragms, all of which add a variety of elements, materials, and connections with unique characteristics.

The NEHRP technical briefs *Seismic Design of Cast-in-Place Concrete Diaphragms, Chords, and Collectors* (NIST, 2010f) and *Seismic Design of Composite Steel Deck and Concrete-filled Diaphragms* (NIST, 2011b) provide guidance on the design, behavior, and analysis of floor diaphragms and, to some extent, collectors. These guides tend to focus on simplified analysis techniques, although they provide some guidance on modeling of diaphragms in linear and nonlinear dynamic analyses. PEER/ATC-72-1 provides additional guidance for diaphragm modeling and analysis assumptions in tall buildings with backstay effects (i.e., seismic force-resisting systems that extend into basements of buildings, and the resulting reactions at the ground floor diaphragm). A recent NEESR project has investigated the seismic performance of floor diaphragms in pre-cast concrete structures, such as ones that experienced failures in the 1994 Northridge earthquake (Fleischman et al., 2013).

Code requirements for diaphragms and collectors generally presume that these elements will remain elastic and allow for simplified analysis and prescriptive design procedures. Diaphragms are generally designed based on force requirements determined from a combination of building code equations (e.g., ASCE/SEI 7 equations to determine inertial loads associated with floor accelerations) and analysis results (forces due to the transfer of forces between elements of the seismic force-resisting system). Collectors are designed to remain elastic for the maximum force that can be developed in the system, calculated by either assuming a fully developed mechanism in the seismic force-resisting system, or amplifying elastic forces by an overstrength factor, Ω.

Although the equations and procedures specified in ASCE/SEI 7 appear to have a rational basis, various studies have suggested that the actual forces developed in diaphragms and collectors can be quite different from analytical predictions. Code requirements are generally considered to be conservative, however, it is unclear if this is truly the case. In some cases, they appear to be overly conservative. In other cases, diaphragm designs may be unconservative if nonlinearities in the seismic force-resisting system or the diaphragm result in forces that are larger than those obtained from elastic analyses. Current approaches also conveniently ignore subassemblage behaviors and interactions (e.g., the effect of topping slabs on collector elements in compression and tension, and the strain incompatibilities that exist between them), which engineers often idealize or ignore. Experimental testing of diaphragms and collectors is less common than testing of other seismic force-resisting elements. Thus, a lack of knowledge about the nonlinear response of diaphragm elements contributes to the prevalence of approximate methods of analysis and design that require further validation.

Diaphragms are not typically modeled as inelastic elements, except when effective stiffness parameters are modified to account for cracking that may occur in concrete slabs under large earthquake demands. When three-dimensional nonlinear dynamic analysis is used in design, diaphragms are generally modeled using kinematic rigid floor constraints or elastic finite elements (e.g., plate or shell elements). Because of this, assumptions regarding the effective stiffness of the diaphragm, the representation of collector elements in the model, and the extraction of diaphragm and collector design forces, are needed. NEHRP technical briefs related to diaphragms (NIST, 2010f; NIST, 2011b) provide some guidance in these areas, and design-friendly software is facilitating the calculation of stress resultants. Recent gains in computational speed and affordable processing power are enabling greater use of finite element models, which make the calculation of diaphragm forces and deformations more straightforward.

Considering current modeling capabilities and design guidance for diaphragms, there are still many unresolved questions. Additional research and guidance is needed in the following areas:

- Model parameters for elastic and inelastic modeling of diaphragms and collectors, considering common diaphragm types and the associated connections between diaphragms, collectors, and the balance of the seismic force-resisting system.
- Analysis and design related to accidental torsion, diaphragm transfer forces in structures with irregularities, and the influence of diaphragm and collector stiffness.
- Selection and scaling of ground motions related to diaphragm and collector force calculations. There is some evidence, for example, that current scaling techniques matching spectral values based on the first mode period of the seismic force-resisting system may overestimate the diaphragm accelerations and forces that are affected by short period response.
- Inelastic deformations and ductility demands, and how they relate to seismic performance objectives and design criteria for diaphragm, collectors, and other components of the building.

Research Initiative 4.9 (divided into two parts) is intended to improve modeling of collector and diaphragm demands in nonlinear dynamic analysis. Part 1 (Initiative 4.9a) is intended to determine when diaphragm behavior is important. Part 2 (Initiative 4.9b) is intended to develop practical guidance and recommendations for implementation.

Proposed Research Initiative 4.9a	
Title	Improve Modeling of Collector and Diaphragm Demands in Nonlinear Dynamic Analysis: Part 1
Objectives	Improve methodologies for explicit inclusion of diaphragms, chords, and collectors in analysis.
Scope	Task 1: Perform a literature review on the influence of diaphragm flexibility and strength on system response. Find circumstances under which it is believed that diaphragm flexibility or inelastic behavior had a significant influence on the performance of real buildings under real earthquakes. Task 2: Identify existing finite element or other modeling strategies that may be utilized for diaphragms, and determine if the elements are adequate. Provide recommendations for new elements and modeling strategies if the current approaches are not adequate.
Estimated Timeline	12 to 24 months
Team	Research team (faculty member and one or more graduate students), overseen by a group of researchers and engineering practitioners
Audience	Researchers; software developers; engineering practitioners
Product	Report summarizing results

Proposed Research Initiative 4.9b	
Title	Improve Modeling of Collector and Diaphragm Demands in Nonlinear Dynamic Analysis: Part 2
Objectives	Provide practical guidance for explicit inclusion of diaphragms, chords, and collectors in analysis, and implementation in engineering practice.
Scope	Task 1: Identify the characteristics of structures for which diaphragm deformations may be important, and assess the influence on response. Task 2: Provide practical recommendations for modeling of diaphragms and collectors.
Estimated Timeline	Approximately 24 months
Team	Research team (faculty member and one or more graduate students), overseen by a group of researchers and engineering practitioners
Audience	Engineering practitioners; software developers; researchers
Product	Report, including recommendations for implementation (e.g., in ASCE/SEI 7 or ASCE/SEI 41)

4.2.5 *Modeling of Vertical Ground Motion Effects in Nonlinear Analysis*

Vertical ground motions are generally not included in nonlinear dynamic analysis because it is assumed that their effect is small relative to the significant overstrength for resisting gravity loads that is present in buildings. This overstrength is associated with the fact that seismic force effects are evaluated under expected loading, whereas gravity design is typically controlled by factored dead and live loads. In some cases, however, dynamic response under vertical ground motions can be significant, as in the case of systems with long spans or long cantilevers. In addition, systems with vertical discontinuities in the seismic force-resisting system, as well as systems with nonductile gravity framing, can be sensitive to the effects of vertical ground motions.

The influence of vertical shaking depends on the frequency content of the ground motion relative to the frequency content of the vertical response, and on the relative phasing of system response and ground motion input. For example, if a building is deforming near its maximum displacement while the ground motion is positive vertical, inertia forces in the vertical direction will compress the columns, adding to the tendency towards P-Δ instability and potential collapse in cases where collapse might not have occurred in absence of vertical ground motion. On the other hand, if the ground motion is negative vertical (moving downward) at the same time that the maximum horizontal displacement is reached, vertical ground motions will have a stabilizing effect that reduces P-Δ instability and the potential for collapse. Spears (2003) studied this effect on a variety of single-degree-of-freedom systems and found that, on average, there was an equal tendency for vertical ground motions to have a detrimental or beneficial effect on response.

From a technical standpoint, the inclusion of vertical ground motions in nonlinear dynamic analysis appears to be straightforward. However, the following issues require careful consideration:

- Structures respond at higher frequencies in the vertical direction than they do in the horizontal direction, so higher frequency response needs to be captured in the analysis. Vertical components of ground motions are typically richer in high frequency content than horizontal components. These factors may require a shorter integration time step than is typically used in analysis for horizontal ground motion, and the ability to capture high frequency modes may require special attention to numerical tolerances and damping.
- Modeling of systems for sensitivity to vertical shaking will require distributed masses in beams, girders, diaphragms, and other horizontal elements, rather than lumped masses concentrated at column nodes, which is common practice in lateral analyses.

- Procedures for selection and scaling of ground motions for design-based analyses (e.g., ASCE/SEI 7) and for collapse analyses (e.g., FEMA P-695) need to be explored, particularly with regard to factors that influence near source effects and the relative intensity of vertical and horizontal shaking.
- The high-frequency characteristics of vertical ground motions lead to questions about the interpretation of high-frequency force demands and their consequences on structural response. For example, high frequency pulses may have time durations that are too short to affect structural response, which could potentially lead to over-conservative interpretations for design. Related to this are questions about soil-structure interaction (SSI) and whether or not SSI is likely to have an effect on vertical ground motions or the definition of vertical foundation input motions.

Considerable debate remains as to the significance of vertical ground motions on structural response. Research Initiative 4.10 (divided into two parts) is intended to explore when vertical ground motions are important, and to provide guidance on best practices for modeling vertical ground motion effects, when necessary.

Proposed Research Initiative 4.10a	
Title	Identify Best Practices for Modeling Vertical Ground Motion Effects in Nonlinear Analysis: Part 1
Objectives	To identify existing cases where vertical ground motions have proven to be important, and review available modeling approaches.
Scope	Task 1: Conduct a literature review on the characteristics and influence of vertical motions, and on circumstances under which it is believed that vertical motions influenced the performance of real buildings under real earthquakes. Task 2: Review modeling approaches to determine how models could be improved to better capture the influence of vertical motions.
Estimated Timeline	Approximately 12 months
Team	Research team (faculty member and one or more graduate students), overseen by a group of researchers and engineering practitioners
Audience	Researchers; software developers; engineering practitioners
Product	Report summarizing results

Proposed Research Initiative 4.10b	
Title	Identify Best Practices for Modeling Vertical Ground Motion Effects in Nonlinear Analysis: Part 2
Objectives	To determine when vertical ground motions are important considerations in the seismic performance of structures, and to establish best practices for modeling structures when vertical ground motions are included.
Scope	Task 1: Expand single-degree-of-freedom system studies (e.g., Spears, 2003) to multi-degree-of-freedom systems, and analyze systems both with and without vertical motions to determine their influence on behavior. Task 2: Determine the circumstances (geological and structural) under which vertical motions are most critical. Provide recommendations for selecting and scaling ground motions when vertical motions are considered. Task 3: Provide practical recommendations for inclusion of vertical accelerations in analysis, and for modeling structures to capture the important effects.
Estimated Timeline	Approximately 24 months
Team	One or more research teams (faculty members and graduate students), overseen by a group of researchers, engineering practitioners, and USGS representatives.
Audience	Engineering practitioners; software developers; researchers
Product	Report documenting results; possible Technical Brief summary of recommendations

4.2.6 Development of Direct (Continuum) Approach for Modeling Soil-Structure Interaction

Soil-structure interaction (SSI) refers to the interaction between the building superstructure, its foundation, and the surrounding soil. Interaction between these components affects the characteristics of the soil-foundation system, the transmission of earthquake ground motions into the structure, and the overall system response. In general, SSI effects are most significant when the superstructure and foundation are stiff relative to the surrounding soil. However, the complexity of the interactions, and dependence on the specific characteristics of the structure, the site, and the input ground motions, make it difficult to generalize.

NIST GCR 12-917-21, *Soil-Foundation-Structure Interaction for Building Structures* (NIST, 2012b), provides a concise summary of SSI principles and guidance for developing SSI models for nonlinear analysis. In NIST GCR 12-917-21, modeling of SSI is characterized by two alternative approaches, referred to as the direct (continuum-based) or indirect (substructure-based) approaches. The direct analysis approach, illustrated in Figure 4-2, entails continuum finite element models of the soil and soil-foundation interface. Ground motions are applied to the system at a transmitting boundary that is sufficiently far away as to avoid being influenced by the building response. In a direct analysis approach, the soil and interface are modeled using fundamental properties to simulate nonlinear behavior of the soil under three-dimensional stress and strain conditions with explicit consideration of pore-water pressure and other effects.

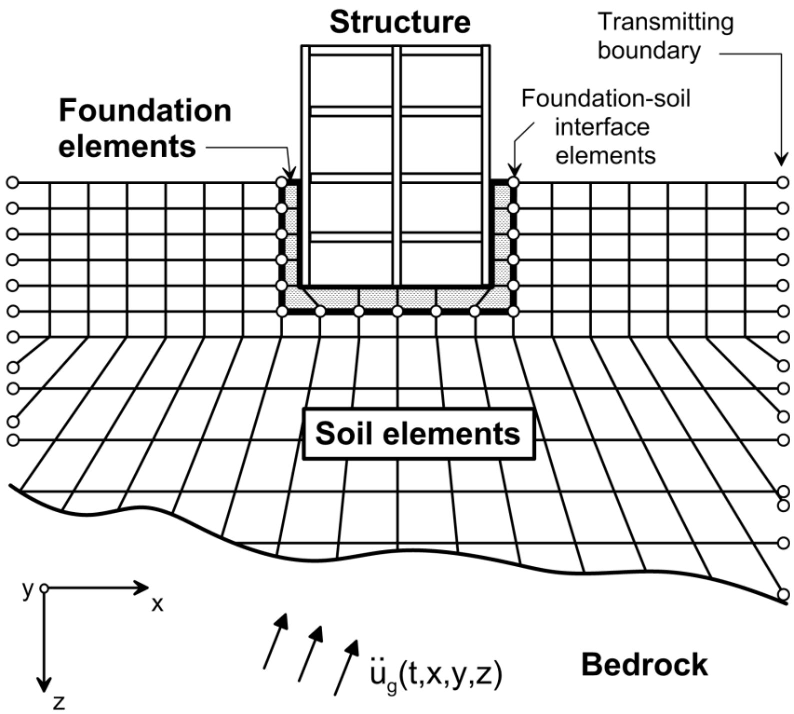

Figure 4-2 Schematic illustration of a direct analysis of soil-structure interaction using continuum modeling by finite elements (NIST, 2012b).

The indirect (substructure) approach, illustrated in Figure 4-3, represents the soil and soil-foundation interface with idealized springs and dashpots, which are calibrated to represent the continuum response. In the indirect approach, ground motions are typically input assuming fully coherent motions based on free-field motions adjusted to foundation input motions (FIM) that account for effects such as variability and incoherence of motions through the soil depth and over the footprint of the building.

When SSI effects are modeled in engineering practice, the indirect approach is most commonly used, since this approach generally requires less modeling and computational effort. The indirect approach, however, is based on simplifying assumptions that have not been validated for all situations encountered in practice, and may not be able to simulate the full range of response of the soil-foundation system. Equivalent properties for soil springs and dashpots, for example, have been developed based on theories and evidence supported by simple soil tests, limited centrifuge and shake table testing, and some field data. The field data is limited with regard to the specific conditions encountered (e.g., soil and foundation types, and structural configuration) and the intensity of earthquake ground shaking.

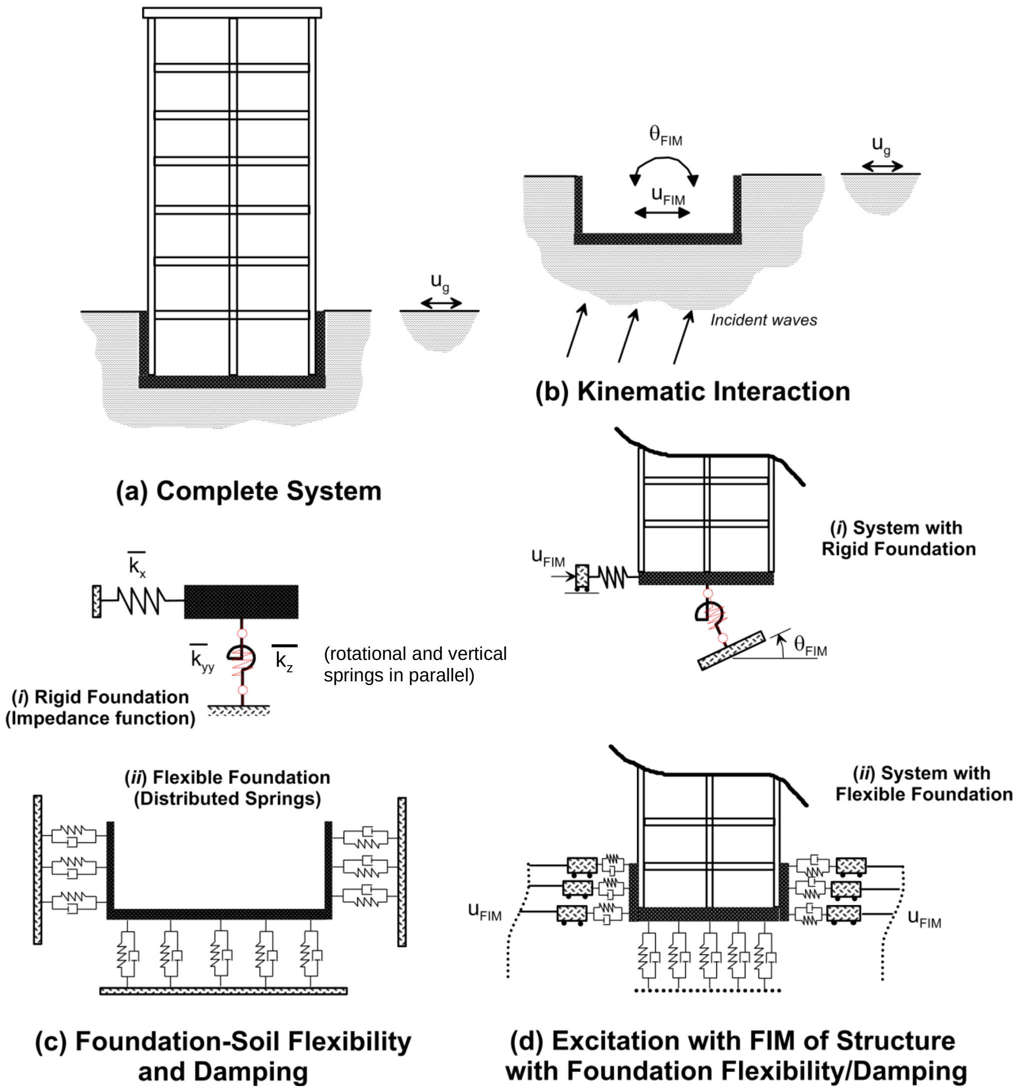

Figure 4-3 Schematic illustration of the indirect (substructure) approach to analysis of soil-structure interaction (NIST, 2012b).

Research Initiative 4.11 is intended to develop improved understanding of direct and indirect methods of SSI analysis as an extension of NIST GCR 12-917-21, which is focused on the indirect (substructure) approach. Work would include assessment of the two methods, and development of guidelines for implementing the direct analysis approach. Case studies would be developed to help identify and illustrate limitations in the indirect (substructure) approach, along with ways to overcome these limitations using a direct analysis approach. Although targeted primarily at the direct analysis approach, a possible outcome of these studies could be improvements and refinements to guidance on indirect (substructure) modeling approaches.

Proposed Research Initiative 4.11	
Title	Develop Guidelines for the Use of Direct and Indirect Modeling of Soil-Structure Interaction
Objectives	• Facilitate improved modeling of soil-structure interaction effects for nonlinear analysis by developing practical guidelines and criteria for direct modeling of soil-structure interaction. • Further validate and calibrate indirect modeling approaches by comparison to more realistic direct modeling methods. • Engage software developers to create improved technologies for creating soil-foundation models and input of ground motions.
Scope	Task 1: Address knowledge gaps that limit the applicability of direct approaches (e.g., specification of incoherent wave fields; kinematic interaction for pile foundations; differences between limiting soil-foundation pressures under relatively rapid seismic conditions versus relatively slow rates of loading). Task 2: Address limitations of direct analysis simulation codes. A principal shortcoming at present is the inability to provide multi-support excitation that can accommodate spatially variable input motions. Task 3: Perform simulations using equivalent-linear (substructure) and fully nonlinear (direct) systems with otherwise similar characteristics. Compare to available data. Identify limits of applicability of both approaches. Task 4: Develop a series of reports that provide: (a) guidelines on implementation of direct modeling of nonlinear SSI; (b) illustrative comparisons of direct and indirect analysis methods; and (c) suggested improvements to indirect modeling of SSI.
Estimated Timeline	Approximately 4 years as a near-term effort to develop improved guidelines based on current technologies; longer-term effort to develop more robust fundamental models
Team	Group of 2-3 research teams (faculty member and graduate student) in collaboration with software code developers, overseen by a group of researchers and engineering practitioners
Audience	Researchers; engineering practitioners
Product	Report series

Chapter 5
Computational Technologies

This chapter addresses inefficiencies in nonlinear dynamic analysis model development, computation, and assessment of results. Proposed research and development initiatives are focused in the areas of computational advancements, model generation, and data management and interpretation. Computational advancements address the speed of computation and robustness (reliability of convergence) of computation. Model generation includes the process by which mathematical models of the structure are created, and ways in which software can assist in model development through integration with Building Information Modeling (BIM). Data management and interpretation includes tools for querying analytical data, verifying and validating analysis results, and performing limited reanalysis. When implemented into commercially available software, results from these initiatives have the potential to improve the ease and efficiency with which nonlinear analysis can be used in design.

5.1 Computational Advancements through High-Performance Computing

Nonlinear dynamic analysis is extremely demanding on computational resources, both in terms of solution time and the storage and management of data. For design applications, current practice (e.g., ASCE/SEI 7; ASCE/SEI 41; PEER/ATC-72-1; and LATBDC, 2011) includes the use of three-dimensional models that are subjected to at least seven ground motion pairs. Depending on the size and complexity of the model, such analyses can take several hours to several days, even on the most powerful personal computers currently available. Management and querying of the output data can also be a formidable task.

Computational requirements in the future will continue to increase with new modeling techniques and increasing model complexity. Many of the research and development initiatives outlined in other chapters of this report are likely to add to future computational demands:

- Inclusion of vertical ground motions will require refined modeling (adding degrees of freedom) and shorter integration time steps to capture the higher frequency response of the system.
- Refined modeling of floor diaphragms and soil-foundation systems will add hundreds (or thousands) of degrees of freedom. The modeling complexity and

convergence characteristics of the nonlinear solution are further challenged if inelastic effects are explicitly modeled in these elements.

- Explicit modeling of uncertainty (including accidental torsion) and utilization of nonlinear analysis to explore alternative design solutions will likely increase the required number of analyses and data management needs by at least an order of magnitude.

Recommended improvements to existing procedures, including upcoming changes to Chapter 16 in ASCE/SEI 7 (to be published in 2016), will likely increase the number of ground motions required for analysis. The current proposal increases the recommended number of motions from seven to eleven. Other improvements consider inclusion of the gravity system in the analysis, which will add hundreds of degrees of freedom. Additionally, analysis for the Maximum Considered Earthquake (MCE) event will increase the degree of nonlinearity, leading to increased solution times and higher likelihood of convergence problems.

Collapse assessment using FEMA P-695 is based on analysis with 44 ground motions scaled to produce collapse (generally well beyond MCE-level ground motion intensities). When the FEMA P-695 methodology is used for its intended purpose to quantify code-based design parameters for structural systems, these motions are applied to large suites of building archetypes, and the analysis requirements are even more extreme. To date, published examples of FEMA P-695 analyses have been performed on simplified two-dimensional models, and even these models have required the use of multi-processor computers or computer clusters to perform the computations in a reasonable amount of time.

It seems that the need for more robust analysis of structures is outpacing advancements in computational technology. Despite continued improvement in computer processor speeds, the computational challenges faced in modeling cannot be solved by standard processor advancements alone. Instead, approaches such as multi-threading, parallel processing, distributed computing, and cloud computing will be needed. Some of these approaches may be more amenable to certain solution methods than others (e.g., explicit versus implicit methods), which may suggest directions for future emphasis in software development. The use of specialized chipsets, such as Graphical Processor Units (GPUs) optimized for gaming, should be explored. Various forms of "soft computing" should also be considered, including the use of Artificial Neural Networks (Lagaros and Papadrakadis, 2012).

Structural engineering researchers and software developers are unlikely to perform the fundamental research and development on hardware and software technology that is needed for advancing computational power. However, those involved with structural engineering software development should become familiar with new technologies as they are made available. They should also be aware of hardware and software advancements that are under development or have already been implemented in other fields (e.g., computational fluid dynamics, weather prediction, optimization, economics), and be able to adapt their computational algorithms and approaches to take advantage of these improvements.

Research Initiative 5.1a is intended to review available and upcoming technologies in computational hardware and software in the context of the needs for nonlinear dynamic analysis, and to provide recommendations for new approaches to take full advantage of modern parallel computer architectures.

Proposed Research Initiative 5.1a	
Title	Develop Computational Solution Algorithms for High Performance Parallel Computing
Objectives	Explore and develop ways to take full advantage of modern computational technologies to improve the speed and efficiency of nonlinear dynamic analysis.
Scope	Task 1: Review current and upcoming technology related to processing hardware, and review how other computationally-intensive fields have met computational demands. Task 2: Explore issues related to computation, independent of the processing environment. Items include the efficiency of numerical algorithms, fetching and storing results, and use of artificial neural networks. Assess the relative merits of explicit versus implicit solutions. Task 3: Explore deployment on parallel and distributed systems, including cloud-based platforms and GPU computing. Explore ways to optimize solutions for these platforms. Task 4: Provide recommendations for revised computational algorithms and solvers to take advantage of modern computing systems. Depending on progress, the recommendations may be accompanied by implementations to demonstrate selected approaches.
Estimated Timeline	3 to 4 years for research and development based on adaptation and utilization of existing computational technologies, with longer-term sustained efforts on more fundamental changes to computational approaches and algorithms on new computer architectures.
Team	Principal Investigator with the participation of a research team (one or more faculty members and graduate students) from computer science and mathematics in collaboration with computational software specialists.
Audience	Researchers; software developers; engineering practitioners
Product	Report

Although the current trend appears to be headed towards more sophisticated modeling to achieve more accurate simulation results, an alternate approach might help relieve the pressure of increasing computational demands. Such an approach would involve simplification of analytical models, and compensating for the associated loss in accuracy by running more simulations, explicitly considering uncertainty, and assessing results probabilistically. With this approach, it might be possible to perform hundreds (or thousands) of "good enough" simulations resulting in better information for structural design than would be provided by a few, highly refined analytical models.

Research Initiative 5.1b is intended to investigate the potential for new analysis approaches that are based on probabilistic assessment of a large number of variations of simple models, rather than quasi-deterministic analysis of fewer, more refined models. One of the challenges here is to ensure that the simplified analyses are converging on an unbiased solution. This initiative is related to Research Initiative 4.5 on uncertainty (Chapter 4) and Research Initiative 5.2 on convergence of analyses (Section 5.2).

Proposed Research Initiative 5.1b	
Title	Develop Probabilistic Approaches to Utilize High Performance Cloud Computing
Objectives	Develop new strategies to improve the reliability and efficiency of nonlinear analyses through probabilistic modeling and analysis of simplified system models.
Scope	Task 1: Investigate level of modeling complexity and accuracy needed to obtain acceptable information for seismic design of structural components of various materials (e.g., steel and reinforced concrete). Task 2: Develop a probabilistic framework for analysis using parametric study of numerous simple models in lieu of fewer, more sophisticated models. Task 3: Compare, from a design perspective, the value of information obtained from the detailed models versus the probabilistic approach using simplified models. Task 4: Prepare a summary report.
Estimated Timeline	3 to 4 years
Team	Principal Investigator with the participation of a research team (one or more faculty members and graduate students).
Audience	Researchers; software developers; engineering practitioners
Product	Report

5.2 Convergence

Nonlinear analysis using implicit time-stepping approaches is often inhibited by a failure to obtain a converged solution. Lack of convergence is most likely to occur in systems that are highly nonlinear, particularly when the instantaneous tangent stiffness is not positive-definite as the system approaches collapse. Convergence problems can be intermittent because a system may converge when analyzed using one ground motion, but may not converge using others. Additionally, convergence problems can be caused by a multitude of potentially interacting issues, and the exact reason for non-convergence can be difficult to discern.

The implicit method of analysis solves the time-stepping problem with relatively large time steps (commonly 0.001 to 0.2 seconds) using the Newmark-Beta method, or other similar techniques. Conventional mass, stiffness, and damping matrices represent the properties of the structure. Displacement increments are solved using Gaussian Elimination (or some variant) at each time step. Material and geometric nonlinearities are dealt with by iteration at each time step. Convergence occurs for the time step if the computed residuals (usually force or energy) are less than some pre-specified tolerance. In some cases, the failure to converge within a time step can be alleviated by modification of tolerances, substepping, or nudging the analysis by providing slight modifications to system properties. In other cases, convergence simply cannot be attained. Implicit analysis is currently the most prevalent method used in commercially available software for nonlinear dynamic analysis of building structures (e.g., SAP2000, ETABS, and PERFORM 3D).

An alternate to implicit analysis is explicit analysis. The explicit method solves the time-stepping problem at a large number of very small time steps (on the order of 10^{-5} seconds), which are determined by numerical stability considerations. The solution comprises the repeated application of "acceleration = force/mass" at each degree of freedom, so there is no matrix inversion or iterative convergence. The force is determined from external applied actions and internal effects, based on the current relative displacements and velocities between degrees of freedom connected by elements. Since there are no matrix inversions, the solution technique works for mechanisms, sudden loss of stiffness and strength, and multiple body systems, as well as conventional structures with invertible stiffness matrices. The calculations are based on the current coordinates of the nodes, so large displacements are inherently considered. Several commercial finite element programs (e.g., Abaqus and LS-DYNA) have the capability to use explicit methods, although these are not commonly used in structural engineering practice.

Hidalgo (2013) explains the time-stepping issues for explicit analysis as follows:

> "Since the explicit time step size depends on the length of the smallest element, one excessively small element will reduce the stable time step for the whole model. Mass-scaling can be applied to these small elements to increase their stable time step. The implicit method is not sensitive to such small elements.
>
> Since the explicit time step size depends on the material properties, a nearly incompressible material will also significantly reduce the stable time step. The compressibility of the material can be increased in explicit analysis to achieve a more acceptable solution time. The implicit method is not as sensitive to highly incompressible materials (provided that a mixed formulation is used)."

In some cases it is possible to employ mixed implicit/explicit schemes in which the program alters techniques automatically.

In some cases, a system will fail to converge for one or more ground motions in a suite of motions, while all of the other motions result in convergence. There is some question as to whether non-converged solutions are an acceptable analytical result, or whether they should be disregarded. In some cases they have been treated as collapse. Non-converged solutions, however, are different from simulated collapse, which is an explicit outcome of the behavior of a structure. Because there are many possible reasons for non-convergence, non-converged solutions do not provide definitive information on the behavior of a structure.

Research Initiative 5.2 is intended to address issues related to convergence, develop strategies for obtaining convergence in difficult cases, and provide guidance on how non-converged solutions should be handled, when they occur.

Proposed Research Initiative 5.2	
Title	Improve Numerical Convergence of Nonlinear Dynamic Analysis
Objectives	• Provide guidance on best approaches for obtaining converged solutions. • Discuss the implications of dealing with non-converged solutions when the convergence issue cannot be resolved for one or more ground motions in a suite of motions.
Scope	Task 1: Perform a literature search on analysis methodologies, and determine which factors contribute to lack of convergence. Such factors could include a variety of issues related to the basic computational methodology (implicit versus explicit) and how materials and components are modeled. Task 2: Create a series of system models that have challenges related to convergence, determine why convergence is problematic, and develop methods to limit or eliminate non-convergence. Convergence behavior should be examined on a material, component, and structural level. Determine if convergence is related to the level of detail in the model, and whether it can be mitigated by simplifying models or by use of substructuring (submodeling) techniques to isolate problematic local nonlinearities. Examine how convergence is affected by the combination of numerical solution strategies used for particular problems. Task 3: Contrast convergence issues associated with implicit solution methods with the relative advantages and disadvantages of explicit solution methods, where similar challenges have been encountered and overcome in other application areas. Task 4: Develop guidance on ways to identify and eliminate common situations where non-convergence occurs, and on how to interpret non-converged solutions when they occur (i.e., instances where non-convergence may be due to legitimate structural instability as opposed to a pure numerical ill-conditioning). Recommendations should vary depending on the scope of analysis and the extent to which modeling of collapse behavior is the goal.
Estimated Timeline	Approximately 3 years
Team	One or more research teams (faculty members and graduate students)
Audience	Researchers; software developers; engineering practitioners
Product	Report

Improved understanding of numerical convergence and use of explicit solution methods may result in improved computational efficiencies, which is related to Research Initiative 5.1b.

5.3 Model Development and Integration of BIM and Analysis Software

Currently, most major building projects are designed using Building Information Modeling (BIM), which provides a detailed, three-dimensional representation of the structural and nonstructural components of the building. These models are often created early in the design process and updated throughout design. They contain much of the information necessary to perform structural analysis, but there are few, if any protocols to permit automated (or semi-automated) translation of information between BIM and structural analysis models. Although in certain cases it is possible to transfer the basic geometric description of the building from BIM models to the analysis platform, current technology does not allow for subsequent updating of information (i.e., back and forth communication) between BIM models and analysis models.

Considerable effort goes into creating structural analysis models, which are often unique to the structural analysis platform being used. Use of unique structural models is inefficient, since it requires the structural engineer to create two parallel models: one for BIM, and a second for structural analysis. Moreover, the use of nonlinear analysis in particular can become inhibited, because the nonlinear analysis software may require the creation of an additional independent model. Apart from inefficiencies, the creation and tracking of multiple models can lead to errors in design.

The transfer and translation of information between BIM and various software platforms is termed *interoperability*. Structural analysis would be greatly facilitated by standards and protocols for transfer of information between BIM and structural analysis software. In the near term, these standards and protocols would allow for transfer of information that is presently common to both platforms. In the longer term, protocols could be enhanced to include additional information on structural seismic performance that would facilitate more comprehensive performance-based design. Examples of such information include component fragility and consequence functions used to measure performance in FEMA P-58, *Seismic Performance Assessment of Buildings* (FEMA, 2012b).

Research Initiative 5.3 is intended to develop standards and protocols to facilitate the transfer of information between BIM and structural analysis software. This effort should be coordinated with existing industry standards for interoperability and data transfer, such as Industry Foundation Classes (IFCs) maintained by buildingSMART (www.buildingsmart.com).

Proposed Research Initiative 5.3	
Title	Develop Standards and Protocols for Integration of BIM and Analysis Software
Objectives	Develop standards and protocols to facilitate the development of common databases and the transfer of information between BIM software and structural analysis software.
Scope	Task 1: Assemble representatives from key BIM and structural analysis software developers, along with experts in seismic analysis and design, to identify specific issues and the scope of activities. This task could include a workshop to outline schematic solutions for cases where development of standards and protocols would facilitate transfer between BIM and analysis software. Task 2: Undertake the development of standards and protocols (which could take the form of IFCs). Task 3: Engage BIM and structural analysis software developers to review and refine standards, protocols, and IFCs, and monitor their implementation.
Estimated Timeline	Approximately 3 years, including review, refinement, and possible implementation by software developers.
Team	Principal Investigator working in collaboration with additional researchers, engineering practitioners, and software developers.
Audience	BIM and structural analysis software developers
Product	Report including draft standards and protocols for transfer of information between BIM and analysis platforms.

5.4 Data Management and Tools for Querying Data, Validating Results, and Reanalysis

In many cases, only the end result of a nonlinear analysis is reviewed and reported, leading to concerns that other valuable information from the analysis is either ignored or overlooked. In most cases, this occurs because software platforms tend to focus on tools that query data for the minimum level of information required by governing design provisions. For example, criteria in Chapter 16 of ASCE/SEI 7 are based on comparing the average of the story drifts obtained from seven or more ground motion analyses to a specified drift limit. Similarly, criteria in ASCE/SEI 41 are based on comparing component deformations to specified nonlinear deformation limits. There is a tendency (especially in user-friendly, design-oriented user interfaces) to automatically process the data and report the output in terms of whether or not the minimum performance requirements (i.e., acceptance criteria) have been met. This practice assumes that the nonlinear analysis model is robust and reporting accurate information, and that other information is not useful or would not contribute to improving the design.

To improve nonlinear analysis practice, Research Initiative 5.4 is intended to provide guidance on data and information that should be routinely reviewed to ensure that nonlinear analysis results are reliable, and to better inform the design process. Reported information should be suitable for validation of the model, determining conformance with design requirements, and reanalyzing the model if there are any questions or concerns over the results.

Proposed Research Initiative 5.4	
Title	Develop Best Practice Guidelines for Software Data Querying, Visualization, and Reanalysis
Objectives	Promote greater reliability and more effective use of nonlinear dynamic analysis in design through development of best practices for querying and reviewing analysis data. Best practices are intended to promote the development of improved software tools by providing specific recommendations for the types of data that should be accessible to analysis software users.
Scope	Task 1: Determine the following: (a) features that are commonly available in commercial structural analysis software to query results from nonlinear analysis; (b) features that practicing engineers and researchers feel are important to review and query; and (c) examples of data that are reported in research and other literature to validate software and structural response. Task 2: Develop a list of proposed data that should be queried, and illustrations of how these data could be presented to inform design practice. Task 3: Perform trial applications on one or more buildings to illustrate proposed data queries and evaluate whether the proposals meet expectations. Results from trial applications could be presented and reviewed in a workshop setting. Task 4: Develop a report that outlines best practices for data query, presentation, and interpretation to promote reliable and effective use of nonlinear analysis data. Reach out to commercial software developers to encourage implementation.
Estimated Timeline	24 to 36 months
Team	A group of researchers and engineering practitioners with experience in nonlinear analysis, statistics, and data visualization, supported by graduate students or junior engineers.
Audience	Software developers; researchers; engineering practitioners
Product	Report including best practice guidelines

The following types of information are envisioned to be part of the best practice guidelines:

- Response histories of selected demand parameters from the analysis, such as total drifts, story drift ratios, story shears, or floor accelerations plotted versus time, along with hysteretic force-deformation (or stress-strain) component response plots.
- Plots of energy balance in the structure, including energy dissipated through various components and mechanisms in the structure.
- Energy of the real response that is opportunistically absorbed by damping introduced to suppress zero energy modes, in the case of low-order elements of the type most often used in explicit integration models.

- Statistics on selected demand parameters from one or more response history analyses.
- Triggers to identify when certain demand parameter limits or local (internal) equilibrium tolerances are breached, including ways to interrogate them.
- Tools to conveniently integrate stresses or stress resultants across elements, or collections of elements, to facilitate understanding of force transfer mechanisms.

The goal is to facilitate best practices by providing a set of recommended features and information that software developers should make available to engineering practitioners who use their software. It is envisioned that more effective software tools will encourage users to follow best practices. Ideally, the software should operate as an environment for assessing the performance of the structure under consideration, and not merely a collection of unassociated tools. In addition to providing the necessary information, the environment should allow for selected reanalysis to exercise "what if" scenarios in real time.

Development of best practice guidelines should be informed by engineering practitioners with experience in using nonlinear dynamic analysis for design, researchers who are involved in the development of nonlinear analysis tools, and experts with knowledge of statistics and data visualization. Best practices should be informed by trial applications to visualize proposed data and confirmation of whether the proposed ideas are useful to design practice. The end result is intended to be a report outlining best practice guidelines, specifications for software developers, and illustrative applications.

Chapter 6
Guidelines and Standards

6.1 Introduction

To realize the full potential of nonlinear dynamic analysis in performance-based seismic engineering (PBSE), it is necessary to assemble and distill available knowledge into one or more resource documents focused specifically on analysis for seismic assessment and design. Without such documents, new knowledge and information will not be effectively, or consistently, implemented in practice.

Research initiatives in this chapter describe a series of resource documents that are intended to provide comprehensive guidelines for performing nonlinear dynamic analysis of buildings for PBSE. Where appropriate, the proposed documents build upon, or complement, other existing documents for seismic analysis and design, and offer more detailed guidance where none currently exists.

For engineering resource documents and new procedures to be adopted by practicing engineers, it is important that they are vetted through a consensus review process. A consensus review will result in products that are more likely to be widely embraced by the profession, and will provide the necessary foundation for continued improvement in the future. The nature of nonlinear structural analysis is such that there is more than one acceptable approach for modeling any structure, and there are many different structural components and systems to consider. Thus, it will be necessary for resource documents to: (1) outline overarching requirements and objectives for modeling and analysis; (2) refer to other available documents for guidance and procedures, where appropriate; and (3) provide specific details for a limited number of the most common and effective approaches for modeling each type of structural system.

A general template for new analysis guidelines is envisioned, which will be developed and subsequently applied to system-specific guidelines tailored to modeling and analysis of common structural system types. Many of the proposed guideline initiatives are divided into two parts ("a" and "b") to reflect a sequencing of activities in the development of a first draft that is later refined to incorporate information from other initiatives.

New analysis guidelines should specifically address analysis of component response using macro-, meso- and micro-scale models, as well as system modeling issues, including characterization of input ground motions, damping, geometric nonlinearity, foundations, and soil-structure interaction. They should be developed using a statistically rigorous basis to characterize uncertainties in ground motions, structural properties (e.g., mass, stiffness, and strength), structural behavior, and structural analysis. They should address cyclic modeling of components and systems, with emphasis on simulating behavior from the initiation of inelasticity (and damage) up to the onset of collapse, which will require consideration of large inelastic deformations and cyclic strength and stiffness degradation.

To accompany the guidelines, a series of example analyses should be developed to illustrate their application. Examples should include analyses of realistic structures using alternative modeling approaches. They should examine modeling issues and interpretation of results for assessing structural damage and evaluating commonly used acceptance criteria.

The development of limit state (acceptance) criteria extends beyond the main focus of initiatives for improving nonlinear analysis, but without such criteria, analysis results are of limited use for design practice. Establishing limit state criteria involves consideration of the uncertainties inherent in the calculation of demands through nonlinear analysis. Therefore, the calculation of demands and the associated limit state criteria are closely related.

As a result, the development of a framework for establishing limit state criteria is recommended. This framework is intended to identify how criteria should be developed, and how the results of nonlinear dynamic analysis should be used to evaluate performance limit states for PBSE. It is important to note that the development of limit state criteria stops short of specifying specific acceptable risk targets for the criteria, since specification of risk targets involves policy-level decisions, and supporting cost-benefit evaluation of performance limits, which extend far beyond issues of analysis alone. Work in this area is intended to develop a basis upon which building code organizations, policy makers, or other authorities could select appropriate design criteria, which can then be evaluated using nonlinear dynamic analysis procedures in practice.

6.2 Currently Available Guidelines and Standards

The current state-of-the-art for using nonlinear analysis in design practice relies primarily on macro-scale phenomenological models, including concentrated hinge models for beam columns and nonlinear spring models for struts or wall panels. These macro-scale models provide a simplified representation of component response, which is calibrated to test data and is based on simplifying assumptions that limit the applicability of the models. The major appeal of macro-scale models is that they are conceptually simple, easily parameterized, less computationally demanding, and relatively robust.

Several existing resources (summarized below) are available that provide guidance on the use of nonlinear analysis and acceptance criteria for PBSE. New guidelines are envisioned to build on, and extend, the concepts in existing guidelines and standards. However, as mentioned throughout this research and development program, limitations in the state-of-knowledge at the time each was written contribute to ongoing limitations that inhibit the use of nonlinear analysis in design practice. An overview of key existing guidelines and standards, along with a brief summary of their limitations, is as follows:

- ASCE/SEI 41-06, *Seismic Rehabilitation of Existing Buildings* (ASCE, 2007), is the current standard for application of nonlinear analysis in seismic assessment and design of buildings. It is based on predecessor documents, including FEMA 273, *NEHRP Guidelines for the Seismic Rehabilitation of Buildings* (FEMA, 1997), and FEMA 356, *Prestandard and Commentary for the Seismic Rehabilitation of Buildings* (FEMA, 2000a), which were developed specifically to address seismic evaluation and rehabilitation of existing structures. These documents introduced the use of nonlinear analysis and deterministic criteria to assess various limit states on performance. ASCE/SEI 41 emphasizes the use of nonlinear static (i.e., pushover) analysis with lumped-plasticity macro-scale models, and provides acceptance criteria for common seismic force-resisting systems for use with these models. Although primarily intended for existing buildings, ASCE/SEI 41 has become a de facto standard for nonlinear analysis and performance-based design of new buildings, in the absence of other information.

  Extensive use of ASCE/SEI 41 has identified a number of limitations in the procedures, primarily due to its emphasis on nonlinear static analysis and questions regarding the relationship between deterministic component acceptance criteria and overall building performance. Guideline development initiatives are intended to overcome limitations in ASCE/SEI 41 to: (1) address cyclic response characteristics required for nonlinear dynamic analysis; (2) provide transparent acceptance criteria that consider uncertainties in behavior and analysis; and (3) provide guidance to facilitate appropriate use of meso- and micro-scale models, including ways to validate and calibrate these models against experimental data.

- ASCE/SEI 7-10, *Minimum Design Loads for Buildings and Other Structures* (ASCE, 2010), provides general requirements for the use of nonlinear dynamic analysis. In particular, Chapter 16 outlines general requirements for the structural analysis model, the selection and scaling of input ground motions, and acceptance criteria for force-controlled and deformation-controlled components. Guideline development initiatives are intended to provide details that follow the general principles outlined in ASCE/SEI 7.

- NIST GCR 10-917-5, NEHRP Seismic Design Technical Brief No. 4, *Nonlinear Structural Analysis for Seismic Design*, *A Guide for Practicing Engineers*, (NIST, 2010d) provides general guidance on nonlinear analysis, including basic model attributes, considerations for modeling structural components and foundation elements, and considerations in conducting nonlinear static and dynamic analyses. Guideline development initiatives are intended to build on and complement this Technical Brief, providing detailed analysis and modeling information for specific structural systems.
- *Tall Buildings Initiative: Guidelines for Performance-Based Seismic Design of Tall Buildings* (PEER, 2010), along with *An Alternative Procedure for Seismic Analysis and Design of Tall Buildings Located in the Los Angeles Region* (LATBSDC, 2011) provide requirements for assessing serviceability and safety performance of tall buildings, specifically intended for use with nonlinear dynamic analysis. In contrast with ASCE/SEI 7, which relies on design checks under design-level ground motions, these tall building guidelines are based on checking safety at Maximum Considered Earthquake (MCE) level ground motions. They provide specific criteria for analysis, including requirements for selecting and scaling ground motions, permissible damping in nonlinear models, consideration of building torsion, consideration of uncertainties in calculated demand parameters for force-controlled components, and other factors. However, these guidelines stop short of providing acceptance criteria, and refer users to other documents, such as ASCE/SEI 41 or PEER/ATC-72-1 (ATC, 2010). Guideline development initiatives are intended to complement these tall building guidelines, although differences may arise in some areas due to availability of new research information and differences between the needs of tall buildings versus standard-height buildings.
- PEER/ATC-72-1, *Modeling and Acceptance Criteria for Seismic Design and Analysis of Tall Buildings* (ATC, 2010), provides guidance for nonlinear dynamic analysis of tall buildings, including modeling recommendations for concrete and steel moment frames, concrete walls, and concrete slab-column systems. It also provides guidance for considering damping, strength and stiffness degradation, *P*-delta effects, diaphragms, podiums, and foundations. Although developed under an initiative focused on tall buildings, much of the guidance can be generally applied to all structures. Although these guidelines were developed in a process involving review by a group of researchers and engineering practitioners, they have not been vetted through a formal consensus review process. Guideline development initiatives are intended to draw from the PEER/ATC-72-1 recommendations and extend them through a consensus review process for application to seismic force-resisting systems for buildings of all heights.

- NIST GCR 10-917-9, *Applicability of Multi-Degree-of-Freedom Modeling for Design* (NIST, 2010a) and *Supporting Documentation* (NIST, 2010b), build on nonlinear analysis limitations identified in FEMA 440, *Improvement of Nonlinear Static Seismic Analysis Procedures* (FEMA, 2005). NIST GCR 10-917-9 examined deficiencies in current nonlinear dynamic procedures, and explored ways to overcome limitations of nonlinear static procedures related to the participation of higher modes of response, using techniques that rely on structure-specific multi-mode lateral force distributions. NIST GCR 10-917-9 also identified areas for further study, some of which are covered in the research initiatives included in this research and development program. Where appropriate, information from this NIST report, and other relevant reports, should be incorporated into new analysis guidelines.
- FEMA P-751, *2009 NEHRP Recommended Seismic Provisions: Design Examples* (FEMA, 2012a), provides a detailed presentation of linear and nonlinear analyses of a steel frame designed using FEMA P-750, *NEHRP Recommended Seismic Provisions for New Buildings and Other Structures* (FEMA, 2009c). In this document, the example steel frame is fairly realistic, and the nonlinear analysis employs existing analytical tools. The analytical model and analysis results are reviewed in detail, and an in depth comparison of linear and nonlinear analysis results is provided. This document can serve as a model for research initiatives focused on development of analysis guideline examples.

6.3 Relationship between Guideline Development Initiatives and other Research Initiatives

Research advancing nonlinear analysis is ongoing. Available resource documents can only represent the state-of-knowledge at the time of their writing, so they must evolve over time to stay current.

Results from other research initiatives described in this program are expected to contribute to the resulting guidelines. Ideally, all other research initiatives would be completed prior to creation of the guidelines, but this is not feasible. As a result, guideline development initiatives are intended to utilize currently available (or recently developed) information, while providing a framework that will allow for future improvement and refinement as additional information becomes available.

Certain research initiatives identified in other chapters are particularly relevant to the recommended guideline development initiatives. These include:

- Initiatives 3.1 and 3.4, which will identify weaknesses in existing numerical models and provide guidance on model validation.
- Initiatives 4.1, 4.4, 4.6, 4.8, 4.9, 4.10, and 4.11, which will develop improved modeling approaches and criteria for selected aspects of structural behavior (e.g.,

damping, geometric nonlinear effects, response modification devices, accidental torsion, floor diaphragms and collectors, vertical ground motions, and soil-structure interaction).

- Initiative 4.2, which will outline a general concept for extending ASCE/SEI 41 component models to reflect cyclic response characteristics.
- Initiatives 4.3 and 4.7, which will develop improved models for capturing beam-column and slender wall behavior and response.
- Initiative 4.5, which will develop recommendations for assessing the impact of uncertainty on analysis results.

It is expected that the guideline development initiatives will utilize results of previous research, but will require some additional research and development activity in these areas.

6.4 Nonlinear Analysis Guidelines for PBSE

Nonlinear dynamic analysis has only recently become feasible for practical design situations, and information in available design guidelines and standards is generally lacking or incomplete. Therefore, several guideline development initiatives are recommended to address the need for comprehensive guidance and criteria for the effective use of nonlinear dynamic analysis in practice.

Development of guidelines for nonlinear dynamic analysis is complicated by the fact that analysis technologies, and the criteria used to define modeling parameters and limit state acceptance, are still evolving. Therefore, to some extent the guidelines need to confront issues, and, where appropriate, set standards and criteria that are an advancement beyond the current status quo. Although the intent is not necessarily to spawn a new set of codified standards, new guidelines may need to establish procedures and criteria that are different from those in existing guidelines and standards (e.g., ASCE/SEI 7 and ASCE/SEI 41). By looking carefully at the specific issues, the hope is that potential inconsistencies between new guidelines and the underlying reference standards can be reconciled in the future. In this regard, guideline documents may ultimately serve as a mechanism to guide the future development of existing codes and standards, and should be considered as a step in the evolutionary process, rather than an end goal in and of themselves.

It is proposed to develop separate guideline documents for several common structural building systems, where each guideline follows a common approach that is outlined in an over-arching document that addresses global system modeling issues.

Separate guidelines for common structural systems are recommended for a few reasons. First, separate guidelines for specific combinations of lateral and gravity systems will reflect the inherent interaction that should be considered in the analysis.

As this interaction depends on the specific materials and systems, the way that it is treated in analysis may differ significantly. Second, system-specific guidelines will facilitate treatment of tiered approaches to model refinement and enhancement (i.e., progressing from macro- to meso- to micro-scale modeling), which may differ considerably depending on the type of system. Third, although the guidelines may draw from established codified standards, the guideline documents (in their initial form) are not envisioned as stand-alone standards. Rather, they are intended to provide guidance that emphasizes integration of the latest knowledge with nonlinear modeling techniques. Finally, as a practical matter, separating the guidelines into system-specific documents will facilitate the development process, allowing certain efforts to advance ahead of others based on the needs of the profession, the state of knowledge, and currently available analysis technologies. Although asynchronous development may lead to some inconsistencies between documents, these differences will be part of the evolutionary process in which the guidelines, and underlying standards, will invariably change over time as information evolves.

6.4.1 Template for Nonlinear Analysis Guidelines

To facilitate development of system-specific analysis guidelines, Research Initiative 6.1 (split into three parts) is focused on developing a template to be applied in the development of successor guideline documents. This template would develop a common outline and organization for the guidelines, and identify the key components and general principles for each section of a typical guideline document. This effort would be informed by the format and content of other existing guidelines and standards, and might even suggest ways that existing guidelines and standards could evolve to improve their coverage of nonlinear dynamic analysis for design.

It is anticipated that the development of a template will be iterative, with development of an initial template (Initiative 6.1a) that precedes efforts to develop one or more system-specific guideline documents. A revised final version of the template will be developed (Initiative 6.1b) that incorporates feedback from initial development efforts on the system-specific guidelines.

One key consideration is the format in which the guidelines will be published, and how they will be accessed by their intended audiences (e.g., engineering practitioners, researchers, software developers, and code developers). Given that the guidelines are likely to change as new information becomes available (i.e., as research initiatives are completed), it may be necessary to update them on a more regular basis, and traditional technical reports in print format may not be the best way to accomplish this. Therefore, a web-based procedure for developing, accessing, and updating the guidelines could be considered (Initiative 6.1c). Online forums (i.e., WIKIs), like the one used in documentation for OpenSEES, may serve as a starting point (http://opensees.berkeley.edu). Such a platform could also host a series of examples and active learning tutorials. However, before any approach is adopted, it will be necessary to review current approaches and determine the most appropriate platform for dissemination, maintenance, and update of the guidelines.

Proposed Research Initiative 6.1a	
Title	Develop an Initial Nonlinear Analysis Guideline Template
Objectives	Develop a standard template for analysis guideline documents.
Scope	Task 1: Identify critical themes and topics that should be included in the series of recommended analysis guidelines. Task 2: Develop a detailed template for the outline, organization, and content of analysis guideline documents. Task 3: Develop recommendations for the most appropriate way to disseminate, maintain, and update analysis guidelines (this information will be used in Research Initiative 6.1c)
Estimated Timeline	Approximately 12 months
Team	Group of three researchers and engineering practitioners, including one member with experience in writing and publishing on-line documentation.
Audience	NIST program planners; research teams charged with development of system-specific analysis guideline documents.
Product	Analysis guidelines template

Proposed Research Initiative 6.1b	
Title	Update the Nonlinear Analysis Guideline Template
Objectives	Revise the template developed in Research Initiative 6.1a to reflect lessons learned during the guideline development process.
Scope	Task 1: Evaluate the initial template document using feedback from research teams tasked with developing system-specific guideline documents. Task 2: Develop a final analysis guideline template.
Estimated Timeline	Approximately 12 months
Team	Group of three researchers and engineering practitioners
Audience	NIST program planners; research teams charged with development of system-specific analysis guideline documents.
Product	Updated analysis guidelines template

Proposed Research Initiative 6.1c	
Title	Evaluate Web-Based Procedure for Development and Delivery of Analysis Guidelines
Objectives	Establish strategy and schematic design for a web-based procedure (e.g., WIKI) to develop, disseminate, maintain, and update guidelines, validation data, and benchmark models for nonlinear dynamic analysis.
Scope	Task 1: Evaluate the need for a web-based analysis support platform and current web-based distribution capabilities. Task 2: Develop a specification and preliminary implementation (i.e., demonstration) of a web-based analysis support platform. Task 3: Engage focus groups representing the user audience to review and comment on the preliminary web-based analysis support platform. Task 4: Update the preliminary version to complete a Version 1.0 implementation of a web-based analysis support platform.
Estimated Timeline	Approximately 24 months
Team	Group of four technical representatives (research community, practitioner community, building standards community, and software developer community); IT contractor; representatives from NIST (and possibly NEES).
Audience	NIST program planners; research teams charged with development of system-specific analysis guideline documents.
Product	Preliminary specification and Version 1.0 implementation of a web-based analysis support platform.

The following is a preliminary outline illustrating the nature and type of information expected to be included in the analysis guidelines template:

1. **Introduction and Scope.** This section would include a description of the structural system to be modeled, including the inelastic response behavior and mechanisms that are expected to dominate response and should be simulated in the analysis. It should provide an overview of the general types of models (with appropriate distinctions to micro-, meso-, and macro-modes) that are appropriate for modeling the expected inelastic response modes with currently available analysis technologies, including the advantages and disadvantages of the various model types for the specific type of lateral and gravity system that is being covered. The introduction should also include a list of important reference documents, nomenclature, and symbols.

2. **Definition and Interpretation of Demand Parameters.** This section should provide descriptions of demand parameters and other analysis results that are important to performance assessment of the system, including the ease and confidence with which they can be obtained from different types of models. This should include consideration of variability in response associated with uncertainties in demand assessment and damage state criteria. It should include discussion of how the analysis results will be interpreted, either through specified

acceptance criteria for various limit states or as input to damage models for general performance assessment. Two general limit states that are likely to be important include: (1) the initiation of structural damage; and (2) the onset of collapse.

3. **General System Modeling Requirements.** This section should address general system modeling requirements that are common to most building systems. This section is expected to refer to relevant standards (e.g., ASCE/SEI 7, ASCE/SEI 41, and material design standards) and other relevant resources (e.g., NIST, FEMA and other reports) for additional guidance on the following:

   - Characterization of earthquake ground motions, including consideration of how soil- structure interaction effects are captured.
   - Modeling of damping to reflect energy that is dissipated in the building system that is not otherwise captured directly in the hysteretic properties of the structural analysis components or models of other energy dissipating elements or devices.
   - Consideration of modeling uncertainties, where variability in modeling parameters may lead to disproportionate changes in the structural response. This is related to such topics as variability in stiffness and strength of structural components and mass that can lead to accidental torsion, vertical irregularities, or excessive force or deformation demands in certain structural components or subsystems.
   - Modeling of secondary systems, including lateral resistance provided by the gravity framing or significant nonstructural components that are specific to the lateral and gravity system being considered.
   - Consideration of non-simulated deterioration modes, including: (1) whether they are likely to have a significant effect on the structural response at the varying demand levels; and (2) how significant non-simulated deterioration effects are incorporated in the nonlinear analysis.
   - Consideration of numerical modeling issues, such as selection of integration methods and time steps, iterative solution strategies, and numerical convergence tolerance.

4. **Macro-Scale Component Models.** This section should define the macro-scale component models and modeling parameters that are appropriate for modeling the overall structural system or components of the system being considered. Ideally, macro-scale models and modeling parameters will follow the generalized cyclic component model framework defined as a result of Research Initiative 4.2. Definition of the model should include the component response envelope, as well as cyclic response quantities, and consideration of combining component

modeling parameters from ASCE/SEI 41 with other models, or adjustments to capture cyclic response or other characteristics (such as interaction of flexure and shear effects).

5. **Meso-Scale Component Models.** This section should define the meso-scale component models and modeling parameters (e.g., fiber-type hinges with lumped or distributed plasticity) that may be appropriate for modeling the overall structural system or components of the system being considered, including key advantages or disadvantages of meso-scale models compared to macro-scale models. It should also discuss the major modeling considerations associated with the meso-scale models, including:
   - Appropriate levels of mesh refinement at the section, component, or structural level.
   - Instructions how to handle strength-degrading components that may require regularization of the mesh and material models to accurately capture localization effects.
   - Material models, including what aspects of behavior can and cannot be simulated through the material models, and how to accomplish this.
   - Methods and strategies to incorporate macro-scale models or limit state checks for deterioration modes that are not directly simulated by the meso-scale models.
   - Methods to calibrate and validate meso-scale models and modeling parameters to well-established macro-scale models for representative components of the system.
6. **Micro-Scale Component Models.** This section should define the capabilities of available micro-scale models, and the advantages and disadvantages of applying micro-scale models for the system being considered. It should identify why modeling at the micro-scale would be required or desired, and which aspects of behavior can only be captured via micro-scale modeling. Where appropriate, guidance on modeling parameters should be provided, otherwise, links to relevant sources (e.g., research papers, technical manuals, and books) should be provided to identify available guidance on implementing micro-scale approaches for the system being considered.

6.4.2 General and System-Specific Nonlinear Analysis Guidelines

Development of both general and system-specific nonlinear analysis guidelines is recommended for structural systems that are commonly used and for which analysis technologies are sufficiently well-developed to produce reliable results. It is expected that much of the required information will be available in various published sources, including existing guidelines and standards, research papers, and reports.

However, guideline development initiatives anticipate that focused studies may need to be conducted as part of the work to evaluate and reconcile competing models, or to confirm the appropriateness of certain nonlinear modeling recommendations.

Research Initiative 6.2 (divided into two parts) is focused on the development of general modeling guidance and issues related to modeling of building features that are common across multiple structural systems (e.g., foundations and basements).

Proposed Research Initiative 6.2a	
Title	Develop Nonlinear Analysis Guidelines for General Building and Foundation Systems
Objectives	Develop guidelines for nonlinear analysis on modeling issues that are common to most structures.
Scope	Task 1: Develop comprehensive guidance on nonlinear analysis modeling in the following areas: (i) damping, geometric nonlinearity, foundation flexibility, and soil-structure interaction, diaphragms and collectors, interaction between lateral and gravity systems; (ii) influence of nonstructural components on response; (iii) assessment of uncertainty; and (iv) model validation. Task 2: Vet document through a consensus review process.
Estimated Timeline	Approximately 24 months
Team	A group of two researchers and two engineering practitioners assisted by one or more graduate students.
Audience	Engineering practitioners; researchers
Product	Consensus analysis guidelines for general building and foundation systems.

Proposed Research Initiative 6.2b	
Title	Update Nonlinear Analysis Guidelines for General Building and Foundation Systems
Objectives	Update the guidelines developed under Research Initiative 6.2a to reflect the outcome of other research initiatives in this program.
Scope	Task 1: Review latest research results on relevant topics. Task 2: Incorporate the latest research into analysis guidelines for general building and foundation systems.
Estimated Timeline	Approximately 12 months
Team	A group of researchers and engineering practitioners
Audience	Engineering practitioners; researchers
Product	Updated analysis guidelines for general building and foundation systems.

These general guidelines are intended to be used in conjunction with other system-specific guidelines. Using the template developed under Research Initiative 6.1, system-specific guidelines will be developed under Research Initiatives 6.3 to 6.6 for the following systems:

- Steel frame buildings with a ductile moment-resisting frame system, structural steel floor framing, and steel deck with concrete fill floor diaphragms.
- Steel frame buildings with ductile concentrically braced frames or buckling-restrained braced frame systems, steel floor framing, and steel deck with concrete fill floor diaphragms.
- Reinforced concrete buildings with a ductile moment-resisting frame system, concrete beam and one-way slab or two-way flat slab floor framing, and conventional or prestressed reinforcement.
- Reinforced concrete buildings with a reinforced concrete shear wall system, two-way flat slab floor framing, and conventional or prestressed reinforcement.

Proposed Research Initiatives 6.3 to 6.6	
Title	Develop Nonlinear Analysis Guidelines for the following: • Initiative 6.3a: Steel Moment Frames • Initiative 6.3b: Steel Moment Frames (updated) • Initiative 6.4: Steel Braced Frames • Initiative 6.5: Concrete Moment Frames • Initiative 6.6a: Concrete Shear Walls • Initiative 6.6b: Concrete Shear Walls (updated)
Objectives	Develop system-specific guidance for nonlinear analysis addressing component modeling issues that are specific to the system being considered. Address higher-priority systems as soon as possible, and update early guidelines documents to reflect new research findings, when available.
Scope	Task 1: Develop comprehensive system-specific guidelines for nonlinear analysis addressing the following areas: (i) system issues, such as modeling of damping and assessment of uncertainty; (ii) model definition using macro-, meso-, and micro-scale models, including the strengths, weaknesses, and appropriate use of each type of model; and (iii) interpretation of results to assess performance and design the structure. Task 2: Vet documents through a consensus review process.
Estimated Timeline	Approximately 3 years (per document)
Team	A group of two researchers and two engineering practitioners assisted by one or more graduate students (per document).
Audience	Engineering practitioners; researchers
Product	Series of consensus, system-specific analysis guidelines.

This research and development program contains many research initiatives that will take several years to complete. However, the need for practical nonlinear analysis guidance is immediate. Therefore, guidelines development initiatives have been structured to begin work on higher-priority systems as soon as possible (e.g., Initiatives 6.3a and 6.6a), but include provisions for update of these early documents in a later phase of work (e.g., Initiatives 6.3b and 6.6b) when new research becomes available. It is assumed that guidelines on systems that are developed later would be able to incorporate the latest research information directly, and, thus, have not been split into two parts (e.g., Initiatives 6.4 and 6.5).

Once the recommended systems have been addressed, it is envisioned that guidelines for other types of systems (e.g., wood shear walls and masonry shear walls) could be considered.

6.4.3 Nonlinear Analysis Example Problems

Research Initiatives 6.7 to 6.10 recommend the development of example applications to accompany each of the system-specific guidelines. Examples are intended illustrate the application of the guidelines, facilitate understanding, and aid in the implementation and adoption of the guidelines in engineering practice.

Proposed Research Initiatives 6.7 to 6.10	
Title	Develop Example Analyses to Accompany Analysis Guidelines for the following: • Initiative 6.7a: Steel Moment Frame Example • Initiative 6.7b: Steel Moment Frame Example (updated) • Initiative 6.8: Steel Braced Frame Example • Initiative 6.9: Concrete Moment Frame Example • Initiative 6.10a: Concrete Shear Wall Example • Initiative 6.10b: Concrete Shear Wall Example (updated)
Objectives	Provide detailed examples demonstrating the intended application and use of nonlinear analysis guidelines. Update initial analysis examples as their companion guideline documents are updated to reflect new research findings.
Scope	Task 1: Generate example analyses for realistic structures with complexities that challenge the robustness of the guidelines, and challenge the decision-making abilities of the average analyst. Task 2: Present examples in a report, online, or through other dissemination methods.
Estimated Timeline	Approximately 18 months (per document)
Team	One researcher and one engineering practitioners assisted by one or more graduate students (per document).
Audience	Engineering practitioners; researchers
Product	Series of example applications as companion documents to nonlinear analysis guidelines developed under Research Initiatives 6.3 through 6.6.

Structured to mirror the development of the system-specific guidelines, the development of example applications for higher-priority systems includes provision for beginning work as soon as possible (e.g., Initiatives 6.7a and 6.10a), and updating early analysis examples when the corresponding guidelines have been updated to reflect new research findings (e.g., Initiatives 6.7b and 6.10b).

Each example is intended to include a complete nonlinear dynamic analysis of at least one complete building system. Examples may include illustrations of several alternative modeling strategies for portions of buildings or selected components, but need only include a complete nonlinear dynamic analysis of one complete system.

It is important that example analyses address the broad range of component and building configurations, and modeling issues encountered in design practice. Development of example analyses should avoid the following shortcomings that have been observed in previous example applications:

- Only the most basic of example problems are provided, and more complicated analysis issues that are typically encountered in practice are not addressed.
- Overly simplistic assumptions are employed to avoid complex modeling issues.
- Assumptions are not adequately explained, justified, or documented.
- The consequences of various modeling decisions are not discussed.
- Errors or misinterpretations are made, and, as a result, examples do not follow the guidelines they are intended to represent.

It is recommended that example analyses include macro and meso-scale models of multiple components with varying design parameters and representing both existing and new construction. They should discuss the advantages and disadvantages of macro- versus meso-scale modeling, discuss components or structural subassemblages for which micro-scale modeling might be desirable or required, and compare results from macro-, meso- and micro-scale models, as appropriate.

To facilitate their use, it is recommended that example analyses be supported by online materials, including input files and output results from analysis software used in the case studies. Online resources could also include training presentations and recorded webinars.

6.5 Acceptance Criteria for Performance-Based Seismic Engineering

The desired outcome of the nonlinear dynamic analysis for design is the likelihood of the structure, as designed, to meet the intended performance objectives. Thus, recommendations and guidelines for conducting nonlinear dynamic analyses must be accompanied by recommendations and guidelines for employing the results of the analyses in determining if a structure meets the specified acceptance criteria.

Currently, ASCE/SEI 41 provides acceptance criteria for determining the seismic performance of existing structures. Specifically, it does the following:

- Identifies and describes discrete performance states including operational, immediate occupancy, life-safety, and collapse prevention.
- Establishes relationships (albeit, approximate) between demand parameters for individual structural components and acceptance criteria for each of the performance states.
- Establishes a range of performance objectives that link seismic hazard levels with structural performance states. For example, the *Basic Safety Objective* consists of a life-safety performance state for an earthquake ground motion with an approximate 10% chance of exceedance in 50 years (i.e., a design basis earthquake, DBE), and a collapse prevention performance state for an earthquake ground motion with an approximate 2% chance of exceedance in 50 years (i.e., a maximum considered earthquake, MCE).

Although the ASCE/SEI 41 procedures are widely used for both new and existing buildings, there are several well-recognized shortcomings. These include: (1) ambiguity in the definitions of immediate occupancy and life-safety performance levels; (2) tenuous relationships between the local component acceptance criteria and overall building performance; and (3) a deterministic and unsubstantiated relationship between the system performance (component demand parameters) and the earthquake hazard level.

Research Initiative 6.11 is intended to develop a more robust and consistent framework for measuring performance using nonlinear dynamic analysis by building on criteria and concepts contained in currently available guidelines and standards. Criteria must be appropriate for models ranging from macro-scale through micro-scale. It is envisioned that this framework would address:

- Selection and scaling of the ground motions used to characterize earthquake hazard for a specified ground motion intensity.
- The use of nonlinear dynamic analysis results from macro-scale through micro-scale models to determine limit state criteria for individual components related to initiation of damage, onset of collapse, and other significant limit states.
- The use of structural demands (e.g., story drifts), component demands (e.g., chord rotation, hinge rotation, and local strain), and component damage states (e.g., concrete cracking and steel yielding) to determine the performance state of the structure.
- Approaches and criteria for quantifying uncertainty in performance assessment.

Proposed Research Initiative 6.11	
Title	Develop Acceptance Criteria for Nonlinear Dynamic Analysis in PBSE
Objectives	Develop a framework for using the results of nonlinear dynamic analysis, and macro-scale through micro-scale models, to assess whether or not a structure will achieve a specified seismic performance state given a specified level of seismic hazard.
Scope	Task 1: Build on existing guidelines and standards to develop a comprehensive process for assessing the performance state of a structure using nonlinear dynamic analysis results. This will include ground motion selection, assessment of the performance state of individual components, assessment of the performance state of the overall structure, and characterization of uncertainty in the process. Task 2: Develop a report defining acceptance criteria and the process by which nonlinear dynamic analysis results can be used to determine if a structure meets the acceptance criteria. Task 3: Vet document through a consensus review process.
Estimated Timeline	Approximately 3 years
Team	Multiple researchers and engineering practitioners assisted by one or more graduate students.
Audience	Engineering practitioners; researchers
Product	Report

Chapter 7
Summary of Recommended Research and Development Program

7.1 Summary of Vision and Research Initiative Areas

The preceding chapters outline a series of research and development initiatives that are intended to improve the effective use of nonlinear dynamic analysis for performance-based seismic engineering (PBSE). Although the development of guidelines for the use of nonlinear analysis is a key result, development of new knowledge through a series of companion research initiatives is necessary to: (1) identify deficiencies and improve capabilities of nonlinear analysis models; (2) systematically validate and calibrate nonlinear models based on data from experimental tests and performance of real buildings; (3) identify and overcome computational and data management bottlenecks that inhibit the practical use of nonlinear analysis in design practice; and (4) examine ways to effectively communicate and integrate knowledge and best-practices for nonlinear analysis into practice through emerging information technologies.

The recommended research and development program has a variable time horizon. Most research initiatives target problems that can be addressed in the near term (approximately five years). Other initiatives take steps that will inform and enable longer term research and development (approximately ten to fifteen years). It should be emphasized that, by virtue of their near-term practical focus, the research initiatives generally do not include important, fundamental, transformative research work (i.e., "grand challenges") that would serve to change nonlinear simulation technologies for performance-based seismic design in ways that have yet to be envisioned.

This chapter summarizes the overall scope of the recommended research and development program, provides an order-of-magnitude estimate of the budget, and presents a schedule in terms of the relative timing of individual research initiatives. Finally, long-term research needs and opportunities for fundamental advancements in modeling and simulation technologies are presented.

7.2 Summary of Proposed Research Initiatives and Tasks

A total of 31 research topics in four research areas are recommended. Considering initiatives with phasing in multiple parts, there are 51 individual research initiatives in the overall research and development program. These are listed in Table 7-1.

Table 7-1 List of Research Initiatives in the Research and Development Program

No.	Initiative Title
3	*Chapter 3: Verification, Validation, and Calibration*
3.1	Assess Reliability of Current Nonlinear Analysis Methods by Examining Blind Prediction Exercises
3.2a	Develop Best Practices for a Tiered Approach for Verification, Validation, and Calibration of Software
3.2b	Apply the Tiered Approach for Verification, Validation, and Calibration to Software
3.3	Develop Improved Analysis Formulations and Software Based on the Outcome of a Tiered Approach
3.4	Collate and Evaluate Existing Test Data Suitable for Validation and Calibration of Models
3.5a	Develop Loading Protocols for Laboratory Testing to Advance Nonlinear Analysis
3.5b	Identify Best Practices for Testing and Test Data Management for Validation and Calibration of Software
3.5c	Develop a Testing Plan to Address Critical Data Needs for Validation and Calibration of Software
4	*Chapter 4: Modeling Capabilities*
4.1a	Recommend Best-Practice Approach for Modeling Damping Using Current Methods
4.1b	Develop New Inherent Damping Methods
4.2a	Develop a Generalized Cyclic Component Model
4.2b	Calibrate Parameters for a Generalized Cyclic Component Model
4.3a	Develop Phenomenological Beam-Column Models with Degrading P-M_y-M_z Interaction
4.3b	Develop Phenomenological Beam-Column Models with Degrading P-M-V Interaction
4.3c	Develop Phenomenological Slender Wall Models with Degrading P-M-V Interaction
4.4	Improve Modeling of Seismic Isolators, Energy Dissipation Devices, and Systems
4.5a	Characterize Uncertainties in Nonlinear Response Simulation
4.5b	Incorporate Uncertainties into Nonlinear Response Simulation
4.6a	Evaluate Current Approaches for Modeling Geometric Nonlinearities
4.6b	Develop Guidelines on Modeling Geometric Nonlinearities
4.7	Calibrate and Interpret Fiber Models for Beam-Columns and Slender Walls
4.8a	Develop Criteria for Modeling and Design for Accidental Torsion Effects in Buildings: Part 1
4.8b	Develop Criteria for Modeling and Design for Accidental Torsion Effects in Buildings: Part 2
4.9a	Improve Modeling of Collector and Diaphragm Demands in Nonlinear Dynamic Analysis: Part 1
4.9b	Improve Modeling of Collector and Diaphragm Demands in Nonlinear Dynamic Analysis: Part 2
4.10a	Identify Best Practices for Modeling Vertical Ground Motion Effects in Nonlinear Analysis: Part 1
4.10b	Identify Best Practices for Modeling Vertical Ground Motion Effects in Nonlinear Analysis: Part 2
4.11	Develop Guidelines for the Use of Direct and Indirect Modeling of Soil-Structure Interaction

Table 7-1 List of Research Initiatives in the Research and Development Program (continued)

No.	Initiative Title
5	*Chapter 5: Computational Technologies*
5.1a	Develop Computational Solution Algorithms for High Performance Parallel Computing
5.1b	Develop Probabilistic Approaches to Utilize High Performance Cloud Computing
5.2	Improve Numerical Convergence of Nonlinear Dynamic Analysis
5.3	Develop Standards and Protocols for Integration of BIM and Analysis Software
5.4	Develop Best Practice Guidelines for Software Data Querying, Visualization, and Reanalysis
6	*Chapter 6: Guidelines and Standards*
6.1a	Develop an Initial Nonlinear Analysis Guideline Template
6.1b	Update the Nonlinear Analysis Guideline Template
6.1c	Evaluate Web-Based Procedure for Development and Delivery of Analysis Guidelines
6.2a	Develop Nonlinear Analysis Guidelines for General Building and Foundation Systems
6.2b	Update Nonlinear Analysis Guidelines for General Building and Foundation Systems
6.3a	Develop Nonlinear Analysis Guidelines for Steel Moment Frames
6.3b	Update Nonlinear Analysis Guidelines for Steel Moment Frames
6.4	Develop Nonlinear Analysis Guidelines for Steel Braced Frames
6.5	Develop Nonlinear Analysis Guidelines for Concrete Moment Frames
6.6a	Develop Nonlinear Analysis Guidelines for Concrete Shear Walls
6.6b	Update Nonlinear Analysis Guidelines for Concrete Shear Walls
6.7a	Develop Example Analyses to Accompany Analysis Guidelines for Steel Moment Frames
6.7b	Update Example Analyses to Accompany Analysis Guidelines for Steel Moment Frames
6.8	Develop Example Analyses to Accompany Analysis Guidelines for Steel Braced Frames
6.9	Develop Example Analyses to Accompany Analysis Guidelines for Concrete Moment Frames
6.10a	Develop Example Analyses to Accompany Analysis Guidelines for Concrete Shear Walls
6.10b	Update Example Analyses to Accompany Analysis Guidelines for Concrete Shear Walls
6.11	Develop Acceptance Criteria for Nonlinear Dynamic Analysis in PBSE

The initiatives are organized into four research areas consisting of: verification, validation, and calibration (Chapter 3); modeling capabilities (Chapter 4); computational technologies (Chapter 5); and guidelines and standards (Chapter 6).

Verification, validation, and calibration initiatives deal primarily with efforts to establish the reliability of nonlinear analyses using experimental data and other information. These initiatives are intended to improve the level of confidence in nonlinear analysis, and to help establish consensus-based recommendations for model attributes and parameters. Since validation and calibration depend on the availability of data, several of the initiatives entail an assessment of available data, and identification of gaps in data that need to be filled through future research and testing.

Initiatives related to modeling capabilities are intended to improve our understanding of nonlinear behavior, improve mathematical modeling of materials and components, and inform explicit consideration of uncertainty. Initiatives in this area range from fundamental research to an emphasis on implementation. As such, many of these initiatives may be suitable for support (or joint support) from the National Science Foundation (NSF) and other research agencies.

Initiatives related to computational technologies address computational model formulations and software implementation used for nonlinear analysis. Several of these initiatives should include active participation of both research and commercial software developers.

Guideline development initiatives are intended to result in a series of comprehensive, consensus-based nonlinear analysis guidelines, and example applications, to facilitate the use of nonlinear analysis in design practice. They are intended to build upon, or complement, other existing resource documents for seismic analysis and design, and offer more detailed guidance where none currently exists. Given current and emerging information technologies, one initiative is aimed at exploring electronic (i.e., web-based) alternatives for developing and disseminating guidelines, examples, and other supporting information.

7.3 Estimated Budget Requirements

Order-of-magnitude estimates of the budget requirements for each research initiative were developed based on the scope and personnel descriptions provided in Chapters 3 through 6. These are summarized in Table 7-2.

Budgets estimates include costs for: (1) direct technical development, primarily professional and student time; (2) direct management and oversight; (3) other direct costs associated with travel, costs to host meetings, and other costs to conduct and report on the initiatives; and (4) an allowance for organizational overhead. Most of the initiatives will involve teams consisting of researchers working in collaboration with engineering practitioners, and supported by graduate students.

The estimated budget requirement for the overall research and development program is $20.5 million, with the following breakdown between areas of research:

- Verification, validation, and calibration – $4.8 million
- Modeling capabilities – $10.3 million
- Computational technologies – $2.0 million
- Guidelines and standards – $3.5 million

Table 7-2 Estimated Budget Requirements, by Initiative and Research Area

Initiative Number	Direct Technical Development	Direct Management and Oversight	Other direct (e.g., Travel)	Overhead	Total Budget
		Chapter 3: Verification, Validation, and Calibration			
3.1	$227,000	$45,000	$64,000	$118,000	$454,000
3.2a	$163,000	$33,000	$46,000	$85,000	$327,000
3.2b	$151,000	$30,000	$42,000	$78,000	$301,000
3.3	$1,069,000	$214,000	$299,000	$556,000	$2,138,000
3.4	$204,000	$41,000	$57,000	$106,000	$408,000
3.5a	$373,000	$75,000	$104,000	$194,000	$746,000
3.5b	$70,000	$14,000	$19,000	$36,000	$139,000
3.5c	$139,000	$28,000	$39,000	$72,000	$278,000
Subtotal					***$4,791,000***
		Chapter 4: Modeling Capabilities			
4.1a	$150,000	$30,000	$42,000	$78,000	$300,000
4.1b	$540,000	$110,000	$150,000	$280,000	$1,080,000
4.2a	$203,000	$40,000	$57,000	$104,000	$404,000
4.2b	$187,000	$37,000	$53,000	$96,000	$373,000
4.3a	$500,000	$100,000	$140,000	$260,000	$1,000,000
4.3b	$500,000	$100,000	$140,000	$260,000	$1,000,000
4.3c	$500,000	$100,000	$140,000	$260,000	$1,000,000
4.4	$250,000	$50,000	$69,000	$130,000	$499,000
4.5a	$200,000	$41,000	$58,000	$105,000	$404,000
4.5b	$390,000	$79,000	$112,000	$205,000	$786,000
4.6a	$70,000	$14,000	$19,000	$36,000	$139,000
4.6b	$100,000	$20,000	$28,000	$52,000	$200,000
4.7	$270,000	$54,000	$76,000	$140,000	$540,000
4.8a	$102,000	$20,000	$28,000	$52,000	$202,000
4.8b	$208,000	$41,000	$58,000	$108,000	$415,000
4.9a	$102,000	$20,000	$28,000	$52,000	$202,000
4.9b	$208,000	$41,000	$58,000	$108,000	$415,000
4.10a	$102,000	$20,000	$28,000	$52,000	$202,000
4.10b	$208,000	$41,000	$58,000	$108,000	$415,000
4.11	$340,000	$68,000	$95,000	$180,000	$683,000
Subtotal					***$10,259,000***

Table 7-2 Estimated Budget Requirements, by Initiative and Research Area (continued)

Initiative Number	Direct Technical Development	Direct Management and Oversight	Other direct (e.g., Travel)	Overhead	Total Budget
Chapter 5: Computational Technologies					
5.1a	$160,000	$30,000	$45,000	$85,000	$320,000
5.1b	$160,000	$30,000	$45,000	$85,000	$320,000
5.2	$283,000	$57,000	$79,000	$147,000	$566,000
5.3	$139,000	$28,000	$39,000	$72,000	$278,000
5.4	$239,000	$48,000	$67,000	$124,000	$478,000
Subtotal					***$1,962,00***
Chapter 6: Guidelines and Standards					
6.1a	$35,000	$7,000	$10,000	$18,000	$70,000
6.1b	$35,000	$7,000	$10,000	$18,000	$70,000
6.1c	$140,000	$30,000	$40,000	$70,000	$280,000
6.2a	$100,000	$20,000	$28,000	$52,000	$200,000
6.2b	$60,000	$12,000	$17,000	$31,000	$120,000
6.3a	$100,000	$20,000	$28,000	$52,000	$200,000
6.3b	$60,000	$12,000	$17,000	$31,000	$120,000
6.4	$160,000	$32,000	$45,000	$83,000	$320,000
6.5	$160,000	$32,000	$45,000	$83,000	$320,000
6.6a	$100,000	$20,000	$28,000	$52,000	$200,000
6.6b	$60,000	$12,000	$17,000	$31,000	$120,000
6.7a	$40,000	$8,000	$11,000	$21,000	$80,000
6.7b	$40,000	$8,000	$11,000	$21,000	$80,000
6.8	$80,000	$16,000	$22,000	$42,000	$160,000
6.9	$80,000	$16,000	$22,000	$42,000	$160,000
6.10a	$40,000	$8,000	$11,000	$21,000	$80,000
6.10b	$40,000	$8,000	$11,000	$21,000	$80,000
6.11	$408,000	$82,000	$114,000	$212,000	$816,000
Subtotal					***$3,476,000***

7.4 Priorities for Research Planning

In general, few of the initiatives depend on others to any significant degree, meaning that there is no strong critical path to the proposed research and development objectives. It could be argued that guideline development initiatives should occur after key questions have been resolved through other research initiatives. Selected guideline initiatives have been targeted for early development for two reasons: (1) to address immediate needs for design practice; and (2) to provide a framework that will help to confirm specific areas where current information and criteria are lacking, and steer the supporting research initiatives toward more specific and impactful outcomes.

Research initiatives have been grouped into three phases based on a combination of: (1) logical sequencing of activities; (2) importance of the research topic; and (3) potential for impact on design practice. Phase 1 initiatives (Table 7-3) represent those initiatives judged to be of highest importance and impact. Phase 2 initiatives (Table 7-4) represent initiatives that follow up on preliminary work conducted in Phase 1, or are judged to be of lesser urgency. Several initiatives have a "Part 1" in Phase 1 and a corresponding "Part 2" in Phase 2, where the Phase 1 work is focused on collecting and distilling information that is currently available, and the Phase 2 work tends to involve studies to develop new (original) data and information. It is envisioned that the guidelines developed in Phase 1, for example, will need to be revisited and updated in Phase 2 to incorporate new information developed under other research initiatives conducted in Phase 1. Phase 3 initiatives (Table 7-5) involve fundamental research studies that are likely to require longer duration and more funding. These are presented separately, not because of their relative priority or importance, but, rather, because they may be more amenable to funding from NSF, or other partner agencies, whose mission is more focused on fundamental advancements in science and engineering.

The columns labeled "Effort/Timing" provide an estimate of the duration, along with suggested timing (over a five year period) of when the projects could be implemented. Durations are based on the actual estimated research and development time for a project, and do not include additional time that may be required for securing program funding and assembling teams (on the front end), and reviewing and disseminating final products (on the back end). The actual timing for implementation of the individual research initiatives will depend on available financial and personnel resources.

As summarized in Tables 7-3 through 7-5, the estimated budgets for each phase is as follows:

- Phase 1 – $7.0 million
- Phase 2 – $6.5 million
- Phase 3 – $7.0 million

Table 7-3 Phase 1 Initiatives, Presented in Order of Priority, with Estimated Budget and Recommended Phasing

	Phase 1	Effort/Timing					
No.	*Initiative Title*	*1*	*2*	*3*	*4*	*5*	*$(K)*
6.1a	Develop an Initial Nonlinear Analysis Guideline Template	■	■				70
6.1c	Evaluate Web-Based Procedure for Development and Delivery of Analysis Guidelines		■	■			280
6.2a	Develop Nonlinear Analysis Guidelines for General Building and Foundation Systems	■	■				200
6.3a	Develop Nonlinear Analysis Guidelines for Steel Moment Frames	■	■				200
6.6a	Develop Nonlinear Analysis Guidelines for Concrete Shear Walls	■	■				200
6.7a	Develop Example Analyses to Accompany Analysis Guidelines for Steel Moment Frames		■				80
6.10a	Develop Example Analyses to Accompany Analysis Guidelines for Concrete Shear Walls		■				80
3.1	Assess Reliability of Current Nonlinear Analysis Methods by Examining Blind Predictions	■	■				454
3.2a	Develop Best Practices for a Tiered Approach for Verification, Validation, and Calibration	■					327
3.2b	Apply the Tiered Approach for Verification, Validation, and Calibration to Software		■	■			301
3.4	Collate and Evaluate Existing Test Data Suitable for Validation and Calibration of Models	■	■	■			408
3.5a	Develop Loading Protocols for Laboratory Testing to Advance Nonlinear Analysis		■	■	■	■	746
3.5b	Identify Best Practices for Testing and Test Data Management for Validation and Calibration				■		139
3.5c	Develop a Testing Plan to Address Critical Data Needs for Validation and Calibration			■	■		278
4.1a	Recommend Best-Practice Approach for Modeling Damping Using Current Methods	■	■				300
4.6a	Evaluate Current Approaches for Modeling Geometric Nonlinearities	■	■				139
4.2a	Develop a Generalized Cyclic Component Model		■	■	■		404
4.7	Calibrate and Interpret Fiber Models for Beam-Columns and Slender Walls	■	■	■			540
4.8a	Develop Criteria For Modeling and Design for Accidental Torsion Effects in Buildings: Part 1	■	■				202
4.9a	Improve Modeling of Collector and Diaphragm Demands in Nonlinear Analysis: Part 1	■	■				202
4.10a	Identify Best Practices for Modeling Vertical Ground Motion Effects: Part 1	■	■				202
4.5a	Characterize Uncertainties in Nonlinear Response Simulation	■	■				404
5.2	Improve Numerical Convergence of Nonlinear Dynamic Analysis	■	■	■			566
5.3	Develop Standards and Protocols for Integration of BIM and Analysis Software		■	■	■		278
	PHASE 1 – TOTAL ESTIMATED BUDGET						**$7,000**

Table 7-4 Phase 2 Initiatives, Presented in Order of Priority, with Estimated Budget and Recommended Phasing

	Phase 2	Effort/Timing					
No.	*Initiative Title*	*1*	*2*	*3*	*4*	*5*	*$(K)*
6.1b	Update the Nonlinear Analysis Guideline Template			■	■		70
6.2b	Update Nonlinear Analysis Guidelines for General Building and Foundation Systems				■	■	120
6.3b	Update Nonlinear Analysis Guidelines for Steel Moment Frames				■	■	120
6.4	Develop Nonlinear Analysis Guidelines for Steel Braced Frames			■	■	■	320
6.5	Develop Nonlinear Analysis Guidelines for Concrete Moment Frames			■	■	■	320
6.6b	Update Nonlinear Analysis Guidelines for Concrete Shear Walls				■	■	120
6.7b	Update Example Analyses to Accompany Analysis Guidelines for Steel Moment Frames					■	80
6.8	Develop Example Analyses to Accompany Analysis Guidelines for Steel Braced Frames					■	160
6.9	Develop Example Analyses to Accompany Analysis Guidelines for Concrete Moment Frames					■	160
6.10b	Update Example Analyses to Accompany Analysis Guidelines for Concrete Shear Walls					■	80
6.11	Develop Acceptance Criteria for Nonlinear Dynamic Analysis in PBSE		■	■	■		816
4.6b	Develop Guidelines on Modeling Geometric Nonlinearities			■	■	■	200
4.2b	Calibrate Parameters for a Generalized Cyclic Component Model			■	■	■	373
4.4	Improve Modeling of Seismic Isolators, Energy Dissipation Devices, and Systems			■	■		499
4.8b	Develop Criteria For Modeling and Design for Accidental Torsion Effects in Buildings: Part 2			■	■	■	415
4.9b	Improve Modeling of Collector and Diaphragm Demands in Nonlinear Analysis: Part 2			■	■	■	415
4.10b	Identify Best Practices for Modeling Vertical Ground Motion Effects: Part 2			■	■	■	415
4.11	Develop Guidelines for the Use of Direct and Indirect Modeling of Soil-Structure Interaction		■	■	■	■	683
5.1a	Develop Computational Solution Algorithms for High Performance Parallel Computing		■	■	■	■	320
5.1b	Develop Probabilistic Approaches to Utilize High Performance Cloud Computing		■	■	■	■	320
5.4	Develop Best Practice Guidelines for Software Data Querying, Visualization, and Reanalysis			■	■	■	478
	PHASE 2 – TOTAL ESTIMATED BUDGET						**$6,484**

Table 7-5 Phase 3 Initiatives, of Possible Interest to Partner Organizations, with Estimated Budget and Recommended Phasing

	Phase 3	Effort/Timing					
No.	*Initiative Title*	*1*	*2*	*3*	*4*	*5*	*$(K)*
3.3	Develop Improved Analysis Formulations and Software Based on a Tiered Approach		■	■	■	■	2,138
4.1b	Develop New Inherent Damping Methods		■	■	■	■	1,080
4.3a	Develop Phenomenological Beam-Column Models with Degrading P-M_y-M_z Interaction	■	■	■	■		1,000
4.3b	Develop Phenomenological Beam-Column Models with Degrading *P-M-V* Interaction	■	■	■	■		1,000
4.3c	Develop Phenomenological Slender Wall Models with Degrading *P-M-V* Interaction	■	■	■	■		1,000
4.5b	Incorporate Uncertainties into Nonlinear Response Simulation		■	■	■	■	786
	PHASE 3 – TOTAL ESTIMATED BUDGET						**$7,004**

Although each of the initiatives is listed separately, there may be economies of scale that could be achieved by grouping certain initiatives into larger projects, or sets of coordinated projects. For example, in Phase 1, two possible groupings for larger coordinated projects are:

- Guideline Development – Initiatives 6.1a, 6.2a, 6.3a, 6.6a, 6.7a, 6.10a
- Modeling Techniques and Criteria – Initiatives 4.1a, 4.6a, 4.8a, 4.9a, 4.10a

7.5 Key Collaborators

Although it is envisioned that NIST would likely implement the overall research and development program, the objectives of the program would benefit from support, interaction, and coordination with other Federal agencies, representative industry organizations, and codes and standards development organizations.

For example, initiatives that involve research and development of a more fundamental nature may be of interest to the National Science Foundation (NSF), through the Network for Earthquake Engineering Simulation (NEES), directorates that support high-performance computing, or other related programs. These include Phase 3 initiatives, but could also include other initiatives.

Guideline development initiatives are similar to efforts that have been supported by the Federal Emergency Management Agency (FEMA) in the past, as part of their mission of hazard mitigation. Some of these documents have been adopted and carried forward by the American Society of Civil Engineers (ASCE), and ASCE may be interested in doing so again in the future. In addition, other material and industry organizations, such as the American Institute of Steel Construction (AISC), the American Concrete Institute (ACI), the Pankow Foundation, and others may be interested in collaborating and supporting the implementation of nonlinear analysis through guidelines and standards.

7.6 Implementation of the Research and Development Program

The program includes research initiatives that will occur in the near term (approximately five years) and longer term (approximately ten to fifteen years). The scope of the initiatives, recommended team, projected schedule, and order of magnitude budget estimates are based on the best present knowledge at this time. It is likely that future research and development will provide new information that could change the team, schedule, or budget requirements for individual research initiatives as they have been outlined herein, especially in the longer term. Future implementation of the program should consider the current state of knowledge and context for nonlinear dynamic analysis at the time that individual research initiatives are being considered for funding, and adjust the recommendations in this report accordingly.

7.7 Implementation of Results in Codes, Standards, Software, and Practice

In general, the initiatives stop short of implementation of recommendations in building codes and standards, or implementation of new modeling formulations in commercially developed software. Instead, the intent is that the products from research initiatives will be published as reports, papers, or electronic media, and disseminated for use. Aspects related to software implementation could be examined in open source platforms (e.g., OpenSees) from which details of the implementation would be accessible to commercial software developers or others who are interested. It is envisioned that, where appropriate, the resulting ideas, findings, and recommendations would be incorporated into codes, standards, software, and engineering practice by interested users.

7.8 Long-Term Challenges and Opportunities

Research initiatives outlined in this program are focused on research and development to expand, validate, and improve analysis technologies that are currently in use. Although they are expected to have a large impact on analysis practice in the near-term future, there are important challenges and opportunities for fundamental advancement of computational simulation methods that are not captured. These include the following:

- Significant improvements are foreseeable using new approaches to simulating structural materials, components, and systems at a more fundamental level than analysis methods in use today. Continued improvements in computational finite element methods offer one means toward achieving this, including extensions to mesh-less methods and from continuum constitutive mechanics to crystal plasticity and other detailed representations of materials. But other methods, such as discrete element methods, which are becoming more practical with advances in computing technologies, may offer more scalable and reliable approaches to simulate behavior at more fundamental levels.

- Along with more advanced analysis formulations, there is a corresponding need for more accurate and complete characterization of structural materials and geo-materials under multi-axial stress and strain states, including characterization of interfaces between materials.
- Given the dramatic growth in cyber-technologies (including computational power, data management and mining, artificial intelligence, and visualization), there are tremendous opportunities to develop enhanced building information model databases to integrate structural analysis with structural design, construction, and performance assessment. However, it is not possible to capitalize on these opportunities by simply extending current approaches. Instead, this will require fundamental rethinking of how to represent structural systems, streamline (automate) analysis, and use optimization and other techniques to facilitate design decision-making.
- The reliability and accuracy of building performance assessment can be dramatically improved through more complete models of soil-structure interaction, interaction of structural and non-structural building components, and characterization of input ground motions. Aside from making the analysis results more reliable, these enhanced modeling capabilities will present new design options for cost-effective improvements to building performance.

Although some of these ideas may seem impractical or inappropriate for design practice today, it is important to recognize that nonlinear analysis is a relatively new development in structural engineering practice. Nonlinear analysis technologies that are just now becoming commonplace can trace their origins to pioneering research of the 1960s through the 1980s, which was a time when computational capabilities limited their application to simple research exercises. As a result, the long-term challenges of today should not be viewed from the context of current practice, but rather with a view toward the computing and information technologies, and improved understanding of earthquake hazard and building performance, that will emerge over the next decades.

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