Quantification of Building Seismic Performance Factors

FEMA P695 / June 2009

FEMA

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Prepared by

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Foreword

The Federal Emergency Management Agency (FEMA) has the goal of reducing the ever-increasing cost that disasters inflict on our country. Preventing losses before they happen by designing and building to withstand anticipated forces from these hazards is one of the key components of mitigation, and is the only truly effective way of reducing the cost of these disasters.

As part of its responsibilities under the National Earthquake Hazards Reduction Program (NEHRP), and in accordance with the National Earthquake Hazards Reduction Act of 1977 (PL 94-125) as amended, FEMA is charged with supporting mitigation activities necessary to improve technical quality in the field of earthquake engineering. The primary method of addressing this charge has been supporting the investigation of seismic and related multi-hazard technical issues as they are identified by FEMA, the development and publication of technical design and construction guidance products, the dissemination of these products, and support of training and related outreach efforts. These voluntary resource guidance products present criteria for the design, construction, upgrade, and function of buildings subject to earthquake ground motions in order to minimize the hazard to life for all buildings and increase the expected performance of critical and higher occupancy structures.

The linear design procedure contained in modern building codes is based on the concept of converting the complicated nonlinear dynamic behavior of a building structure under seismic loading to an equivalent linear problem. The design process starts with the selection of a basic seismic force resisting system for the structure. The code specifies a series of prescriptive requirements for structures based on each such system. These prescriptive requirements regulate configuration, size, materials of construction, detailing, and minimum required strength and stiffness. These seismic design performance requirements are controlled through the assignment of a series of system response coefficients (R, C_d, Ω_0), which represent the material properties and design detailing of the selected system. Based on the linear dynamic response characteristics of the structure and these response coefficients, design lateral forces are distributed to the building's various structural elements using linear analysis techniques and the resulting member forces and structural deflections are calculated. Members are then proportioned to have adequate capacity to resist the calculated forces in combination with other prescribed loads to ensure that calculated displacements do not exceed maximum specified values.

As the codes have improved over the last several decades in how they address seismic design, one of the results was an expansion of code-approved seismic force resisting systems, with many individual systems classified by the type of detailing used. For each increment in detailing, response coefficients were assigned in the code, based largely on judgment and qualitative comparison with the known response capabilities of other systems. The result is that today's code includes more than 80 individual structural systems, each with individual system response coefficients somewhat arbitrarily assigned. Many of these recently defined structural systems have never been subjected to significant level of earthquake ground shaking and the potential response characteristics and ability to meet the design performance objectives is untested and unknown.

What was needed was a standard procedural methodology where the inelastic response characteristics and performance of typical structures designed to a set of structural system provisions could be quantified and the adequacy of the structural system provisions to meet the design performance objectives verified. Such a methodology would need to directly account for the potential variations in structure configuration of structures designed to a set of provisions, the variation in ground motion to which these structures may be subjected and available laboratory data on the behavioral characteristics of structural elements.

The objective of this publication was to develop a procedure to establish consistent and rational building system performance and response parameters (R, C_d, Ω_0) for the linear design methods traditionally used in current building codes. The primary application of the procedure is for the evaluation of structural systems for new construction with equivalent earthquake performance. The primary design performance objective was taken to minimize the risk of structural collapse under the seismic load of maximum considered earthquake as specified in the current *NEHRP Recommended Provisions for New Buildings and Other Structures* (FEMA 450). Although the R factor is the factor of most concern, displacements and material detailing to achieve the implied design ductilities were also included.

It is anticipated that this methodology will ultimately be used by the nation's model building codes and standards to set minimum acceptable design criteria for standard code-approved systems, and to provide guidance in the selection of appropriate design criteria for other systems when linear design methods are applied. This publication will also provide a basis for future evaluation of the current tabulation of and limitations on code-approved structural systems for adequacy to achieve the inherent seismic performance objectives. This material could then potentially be used to modify or eliminate those systems or requirements that can not reliably meet these objectives.

FEMA wishes to express its sincere gratitude to Charlie Kircher, Project Technical Director, and to the members of the Project Team for their efforts in the development of this recommended methodology. The Project Management Committee consisted of Michael Constantinou, Greg Deierlein, Jim Harris, John Hooper, and Allan Porush. They in turn guided the Project Working Groups, which included Andre Filiatrault, Helmut Krawinkler, Kelly Cobeen, Curt Haselton, Abbie Liel, Jiannis Christovasilis, Jason Chou, Stephen Cranford, Brian Dean, Kevin Haas, Jiro Takagi, Assawin Wanitkorkul, and Farzin Zareian. The Project Review Panel consisted of Maryann Phipps (Chair), Amr Elnashai, S.K. Ghosh, Ramon Gilsanz, Ron Hamburger, Jack Hayes, Rich Klingner, Phil Line, Bonnie Manley, Andrei Reinhorn, and Rafael Sabelli, and they provided technical advice and consultation over the duration of the work. The names and affiliations of all who contributed to this report are provided in the list of Project Participants.

Without their dedication and hard work, this project would not have been possible. The American public who live, work and play in buildings in seismic areas are all in their debt.

Federal Emergency Management Agency

Preface

In September 2004 the Applied Technology Council (ATC) was awarded a "Seismic and Multi-Hazard Technical Guidance Development and Support" contract (HSFEHQ-04-D-0641) by the Federal Emergency Management Agency (FEMA) to conduct a variety of tasks, including one entitled "Quantification of Building System Performance and Response Parameters" (ATC-63 Project). The purpose of this project was to establish and document a recommended methodology for reliably quantifying building system performance and response parameters for use in seismic design. These factors include the response modification coefficient (R factor), the system overstrength factor (Ω_0), and the deflection amplification factor (C_d), collectively referred to as "seismic performance factors."

Seismic performance factors are used to estimate strength and deformation demands on systems that are designed using linear methods of analysis, but are responding in the nonlinear range. Their values are fundamentally critical in the specification of seismic loading. R factors were initially introduced in the ATC-3-06 report, *Tentative Provisions for the Development of Seismic Regulations for Buildings*, published in 1978, and subsequently replaced by the *NEHRP Recommended Provisions for Seismic Regulations for New Buildings and Other Structures*, published by FEMA. Original R factors were based on judgment or on qualitative comparisons with the known response capabilities of seismic-force-resisting systems in use at the time. Since then, the number of systems addressed in current seismic codes and standards has increased substantially, and their ability to meet intended seismic performance objectives is largely unknown.

The recommended methodology described in this report is based on a review of relevant research on nonlinear response and collapse simulation, benchmarking studies of selected structural systems, and evaluations of additional structural systems to verify the technical soundness and applicability of the approach. Technical review and comment at critical developmental stages was provided by a panel of experts, which included representatives from the steel, concrete, masonry and wood material industry groups. A workshop of invited experts and other interested stakeholders was convened to receive feedback on the recommended methodology, and input from this group was instrumental in shaping the final product.

ATC is indebted to the leadership of Charlie Kircher, Project Technical Director, and to the members of the ATC-63 Project Team for their efforts in the development of this recommended methodology. The Project Management Committee, consisting of Michael Constantinou, Greg Deierlein, Jim Harris, John Hooper, and Allan Porush monitored and guided the technical efforts of the Project Working Groups, which included Andre Filiatrault, Helmut Krawinkler, Kelly Cobeen, Curt Haselton, Abbie Liel, Jiannis Christovasilis, Jason Chou, Stephen Cranford, Brian Dean, Kevin Haas, Jiro Takagi, Assawin Wanitkorkul, and Farzin Zareian. The Project Review Panel, consisting of Maryann Phipps (Chair), Amr Elnashai, S.K. Ghosh, Ramon Gilsanz, Ron Hamburger, Jack Hayes, Rich Klingner, Phil Line, Bonnie Manley, Andrei Reinhorn, and Rafael Sabelli provided technical advice and consultation over the duration of the work. The names and affiliations of all who contributed to this report are provided in the list of Project Participants.

ATC also gratefully acknowledges Michael Mahoney (FEMA Project Officer), Robert Hanson (FEMA Technical Monitor), and William Holmes (ATC Project Technical Monitor) for their input and guidance in the preparation of this report, Peter N. Mork and Ayse Hortacsu for ATC report production services, and Ramon Gilsanz as ATC Board Contact.

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Executive Summary

This report describes a recommended methodology for reliably quantifying building system performance and response parameters for use in seismic design. The recommended methodology (referred to herein as the Methodology) provides a rational basis for establishing global seismic performance factors (SPFs), including the response modification coefficient (R factor), the system overstrength factor (Ω_0), and deflection amplification factor (C_d), of new seismic-force-resisting systems proposed for inclusion in model building codes.

The purpose of this Methodology is to provide a rational basis for determining building seismic performance factors that, when properly implemented in the seismic design process, will result in *equivalent safety against collapse in an earthquake, comparable to the inherent safety against collapse intended by current seismic codes, for buildings with different seismic-force-resisting systems*.

As developed, the following key principles outline the scope and basis of the Methodology:

- It is applicable to new building structural systems.
- It is compatible with the *NEHRP Recommended Provisions for Seismic Regulations for New Buildings and Other Structures* (FEMA, 2004a) and ASCE/SEI 7, *Minimum Design Loads for Buildings and Other Structures*, (ASCE, 2006a).
- It is consistent with a basic life safety performance objective inherent in current seismic codes and standards.
- Earthquake hazard is based on Maximum Considered Earthquake ground motions.
- Concepts are consistent with seismic performance factor definitions in current seismic codes and standards.
- Safety is expressed in terms of a collapse margin ratio.
- Performance is quantified through nonlinear collapse simulation on a set of archetype models.

- Uncertainty is explicitly considered in the collapse performance evaluation.

The Methodology is intended to apply broadly to all buildings, recognizing that this objective may not be fully achieved for certain seismic environments and building configurations. Likewise, the Methodology has incorporated certain simplifying assumptions deemed appropriate for reliable evaluation of seismic performance. Key assumptions and potential limitations of the Methodology are presented and summarized.

In the development of the Methodology, selected seismic-force-resisting systems were evaluated to illustrate the application of the Methodology and verify its methods. Results of these studies provide insight into the collapse performance of buildings and appropriate values of seismic performance factors. Observations and conclusions in terms of generic findings applicable to all systems, and specific findings for certain types of seismic-force-resisting systems are presented. These findings should be considered generally representative, but not necessarily indicative of all possible trends, given limitations in the number and types of systems evaluated.

The Methodology is recommended for use with model building codes and resource documents to set minimum acceptable design criteria for standard code-approved seismic-force-resisting systems, and to provide guidance in the selection of appropriate design criteria for other systems when linear design methods are applied. It also provides a basis for evaluation of current code-approved systems for their ability to achieve intended seismic performance objectives. It is possible that results of future work based on this Methodology could be used to modify or eliminate those systems or requirements that cannot reliably meet these objectives.

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