Seismic Performance Assessment of Buildings

Volume 1 – Methodology

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Volume 1 – Methodology

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Cover photograph – Collapsed building viewed through the archway of an adjacent building, 1999 Chi-Chi, Taiwan earthquake (courtesy of Farzad Naeim, John A. Martin & Associates, Los Angeles, California).

Foreword

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

Performance-Based Seismic Design (PBSD) is a concept that permits the design and construction of buildings with a realistic and reliable understanding of the risk of life, occupancy, and economic loss that may occur as a result of future earthquakes. PBSD is based on an assessment of a building's design to determine the probability of experiencing different types of losses, considering the range of potential earthquakes that may affect the structure. The first step involves the selection of a desired performance level by a building owner or regulator. Then an input ground motion, scenario event, or earthquake hazard level is selected for which this performance is to be achieved. A designer then conducts a performance assessment, which is intended to determine if the selected performance level is met, or exceeded, at the selected hazard level. In the PBSD process, the building design is then adjusted until the performance assessment indicates a risk of loss that is deemed acceptable by the building owner or regulator.

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

The FEMA 349 *Action Plan for Performance Based Seismic Design* was published by FEMA in April 2000. It called for a developmental project lasting ten years and requiring an estimated $20 million to $27 million in funding (1998 dollars). FEMA was unable to finance such an undertaking, and the plan was not implemented. During that same time, the three National Science Foundation-funded Earthquake Engineering Research Centers were all performing research related to performance-based seismic design. In particular, the Pacific Earthquake Engineering Research Center (PEER) had made significant progress in this area, and approached FEMA with an interest in assisting in such an effort.

In 2001, FEMA contracted with the Applied Technology Council (ATC) to initiate the Project Planning Phase of a multi-year effort to develop PBSD, following the general approach outlined in the FEMA 349 *Action Plan*. Under this contract, work included the development of a project management process and work plan; conduct of two workshops to receive outside input on project needs and goals; consensus on the definitions of performance to be used as the basis for performance-based seismic design; development of a new Program Plan based on the FEMA 349 *Action Plan*; and initiation of the process for quantifying structural and nonstructural component performance. The Project Planning Phase was completed in 2006 with the publication of FEMA 445, *Next-Generation, Performance-Based Seismic Design Guidelines, Program Plan for New and Existing Buildings*.

In 2006, FEMA then contracted with ATC to initiate Phase 1 development of a seismic performance assessment methodology. This work built upon work completed during the Project Planning Phase, as well as research performed by others, including the three Earthquake Engineering Research Centers and other universities, private industry, various construction materials trade associations, and individual product manufacturers and suppliers who have performed research to facilitate the use of their products and materials in a performance-based design environment. Phase 1 developmental work was completed in 2012 with the publication of this series of volumes collectively referred to as FEMA P-58, *Seismic Performance Assessment of Buildings, Methodology and Implementation*. These volumes include FEMA P-58-1, *Volume 1 – Methodology*, FEMA P-58-2, *Volume 2 – Implementation Guide*, and FEMA P-58-3, *Volume 3 – Supporting Electronic Materials and Background Documentation*. For practical implementation of the methodology, work included the development of an electronic tool, referred to as the *Performance Assessment Calculation Tool*, or PACT, to help capture building inventory data, input a given earthquake shaking probability or intensity, apply specific fragilities and consequences to each building component, and present the results of a large number of runs, or realizations, in a logical format.

Unlike earlier versions of performance-based seismic design, the FEMA P-58 methodology utilizes performance measures that can be understood by decision makers. Performance objectives relate to the amount of damage the building may experience and the consequences of this damage including potential casualties, loss of use or occupancy, and repair and reconstruction costs. They can also be used to assess potential environmental impacts, including generation of waste, expenditure of energy, or creation of greenhouse gases.

Although FEMA is supporting the development of PBSD, there will always be a need for the current prescriptive-based building codes, especially for the majority of buildings designed and constructed with a typical level of engineering involvement. PBSD will be best utilized for critical facilities or other structures where increased performance can be justified, or for buildings that will benefit from additional reliability associated with increased engineering design involvement.

As part of FEMA's ongoing commitment to PBSD, work has begun on the Phase 2 developmental effort, which will use the FEMA P-58 seismic performance assessment methodology to develop performance-based seismic design guidelines and stakeholder guidelines. It is envisioned that this next five-year effort will also capture any necessary improvements to the FEMA P-58 methodology described herein, as it is used in the development of the future design guidelines.

FEMA wishes to express its sincere gratitude to all who were involved in this project and in the development of the FEMA P-58 methodology. The entire development team numbered more than 130 individuals, and it is not possible to acknowledge them all here. However, special thanks are extended to: Ronald Hamburger, Project Technical Director; Robert Bachman, Nonstructural Team Leader; John Hooper, Risk Management Team Leader; Andrew Whittaker, Structural Products Team Leader; William Holmes, Steering Committee Chair; and Jon Heinz, ATC Project Manager. The hard work and dedication of these individuals, and all who were involved in this project, have immeasurably helped our nation move towards making performance-based seismic design a reality, and towards reducing losses suffered by the citizens of our country in future earthquakes.

Federal Emergency Management Agency

Preface

In 2001, the Applied Technology Council (ATC) was awarded the first in a series of contracts with the Federal Emergency Management Agency (FEMA) to develop Next-Generation Performance-Based Seismic Design Guidelines for New and Existing Buildings. These projects would become known as the ATC-58/ATC-58-1 Projects. The principal product under this combined 10-year work effort was the development of a methodology for seismic performance assessment of individual buildings that properly accounts for uncertainty in our ability to accurately predict response, and communicates performance in ways that better relate to the decision-making needs of stakeholders.

This report, *Seismic Performance Assessment of Buildings, Volume 1 – Methodology*, and its companion volumes, together describe the resulting methodology as well as the development of basic building information, response quantities, fragilities, and consequence data used as inputs to the methodology. The procedures are probabilistic, uncertainties are explicitly considered, and performance is expressed as the probable consequences, in terms of human losses (deaths and serious injuries), direct economic losses (building repair or replacement costs), and indirect losses (repair time and unsafe placarding) resulting from building damage due to earthquake shaking. The methodology is general enough to be applied to any building type, regardless of age, construction or occupancy; however, basic data on structural and nonstructural damageability and consequence are necessary for its implementation.

To allow for practical implementation of the methodology, work included the collection of fragility and consequence data for most common structural systems and building occupancies, and the development of an electronic *Performance Assessment Calculation Tool* (PACT) for performing the probabilistic computations and accumulation of losses.

This work is the result of more than 130 consultants involved in the development of the methodology and underlying procedures, collection of available fragility data, estimation of consequences, development of supporting electronic tools, implementation of quality assurance procedures, and beta testing efforts. ATC is particularly indebted to the leadership of Ron Hamburger, who served as Project Technical Director, John Hooper and Craig Comartin, who served as Risk Management Products Team Leaders,

Andrew Whittaker, who served as Structural Performance Products Team Leader, Bob Bachman, who served as Nonstructural Performance Products Team Leader, and the members of the Project Management Committee, including John Gillengerten, Bill Holmes, Peter May, Jack Moehle, and Maryann Phipps.

ATC would also like to thank the members of the Project Steering Committee, the Risk Management Products Team, the Structural Performance Products Team, the Nonstructural Performance Products Team, the Fragility Review Panel, the Validation/Verification Team, and the many consultants who assisted these teams. The names of individuals who served on these groups, along with their affiliations, are provided in the list of Project Participants at the end of this report.

ATC acknowledges the Pacific Earthquake Engineering Research Center (PEER), and its framework for performance-based earthquake engineering, as the technical basis underlying the methodology. In particular, the work of Tony Yang, Jack Moehle, Craig Comartin, and Armen Der Kiureghian in developing and presenting the first practical application of the PEER framework, is recognized as the basis for how computations are performed and losses are accumulated in the methodology.

Special acknowledgment is extended to C. Allin Cornell and Helmut Krawinkler for their formative work in contributing to risk assessment and performance-based design methodologies, and to whom this work is dedicated.

ATC also gratefully acknowledges Michael Mahoney (FEMA Project Officer) and Robert Hanson (FEMA Technical Monitor) for their input and guidance in the conduct of this work, and Bernadette Hadnagy, Ayse Hortacsu, Peter N. Mork, and Laura Samant for ATC report production services.

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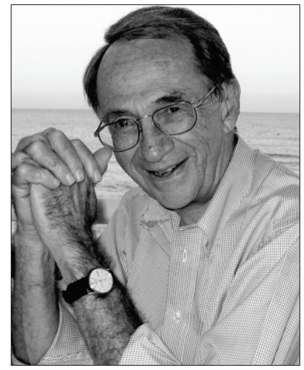
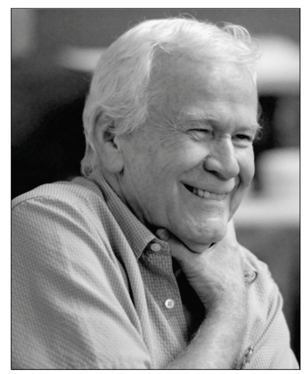
Dedication

The series of reports, collectively referred to as FEMA P-58, *Seismic Performance Assessment of Buildings, Methodology and Implementation*, is dedicated to the memory of C. Allin Cornell and Helmut Krawinkler, longtime faculty colleagues at Stanford University.



C. Allin Cornell



Helmut Krawinkler

Allin brought rigorous mathematical approaches for uncertainty assessment into structural engineering, seismology, and geophysics. His continuous major contributions to risk and reliability analysis over the years have formed the basis for modern seismic risk assessment methodologies. Helmut specialized in structural design and behavior with ground-breaking research on seismic design and nonlinear structural response. His work established principles underlying modern building code provisions and formed the basis of current performance-based design methodologies.

Following the 1994 Northridge earthquake, Allin and Helmut began a close collaboration on the FEMA-funded SAC Steel Project, developing seismic design criteria for steel moment frame construction. In this regard, they were a perfect complement to one another – a combination of rigorous probabilistic thinking with an understanding of nonlinear structural behavior and design. This close collaboration continued to grow in work with the Pacific Earthquake Engineering Research Center (PEER), ultimately leading to the formalization of the PEER framework for performance-based earthquake engineering, the theoretical basis on which this report is based.

In 2000, Allin and Helmut reflected on the ultimate goal of performance-based engineering, "*The final challenge is not in predicting performance or estimating losses; it is in contributing effectively to the reduction of losses and the improvement of safety. We must never forget this.*" Allin and Helmut were true visionaries whose contributions to performance-based design and earthquake engineering are immeasurable. Their professional contributions won them both many accolades, including two of engineering's highest honors – election to the National Academy of Engineering, and receipt of the George W. Housner Medal from the Earthquake Engineering Research Institute. Beyond their professional achievements, they were both delightful, fun-loving, and thoughtful individuals whose spirits live on through their pioneering ideas and the many lives they touched in positive ways.

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