SAC
Steel Project

**Background Document**

# Effects of Partially Restrained Connection Stiffness and Strength on Frame Seismic Performance

## Report No. SAC/BD-99/17

**SAC Joint Venture**
**A partnership of**
**Structural Engineers Association of California (SEAOC)**
**Applied Technology Council (ATC)**
**California Universities for Research in Earthquake Engineering (CUREe)**

By
**Bruce F. Maison**
Structural Engineer
**Kazuhiko Kasai**
Tokyo Institute of Technology
**Arum Mayangarum**
Structural Engineer

Submitted for distribution to
**SAC Joint Venture**
**650-595-1542**
**http://www.sacsteel.org**

**June 2000**

# DISCLAIMER

This document is one of a series documenting background information related to Phase II of the FEMA-funded SAC Steel Project. It is being disseminated in the public interest to increase awareness of the many factors which contribute to the seismic performance of steel moment frame structures. The information contained herein is not for design use and is not acceptable to specific building projects. This report has not been reviewed for accuracy, and the SAC Joint Venture has not verified any of the results presented. **No warranty is offered with regard to the recommendations contained herein, by the Federal Emergency Management Agency, the SAC Joint Venture, the individual joint venture partners, or the partner's directors, members or employees. These organizations and their employees do not assume any legal liability or responsibility for the accuracy, completeness, or usefulness of any of the information, products or processes included in this publication. The reader is cautioned to review carefully the material presented herein and exercise independent judgment as to its suitability for application to specific engineering projects.** This publication has been prepared by the SAC Joint Venture with funding provided by the Federal Emergency Management Agency, under contract number EMW-95-C-4770.

**SAC**
*Steel Project*

*Background Document*

# Effects of Partially Restrained Connection Stiffness and Strength on Frame Seismic Performance

## Report No. SAC/BD-99/17

**SAC Joint Venture**
**A partnership of**
**Structural Engineers Association of California (SEAOC)**
**Applied Technology Council (ATC)**
**California Universities for Research in Earthquake Engineering (CUREe)**

By
**Bruce F. Maison**
Structural Engineer
**Kazuhiko Kasai**
Tokyo Institute of Technology
**Arum Mayangarum**
Structural Engineer

Submitted for distribution to
**SAC Joint Venture**
**650-595-1542**
**http://www.sacsteel.org**

**June 2000**

# THE SAC JOINT VENTURE

SAC is a joint venture of the Structural Engineers Association of California (SEAOC), the Applied Technology Council (ATC), and California Universities for Research in Earthquake Engineering (CUREe), formed specifically to address both immediate and long-term needs related to solving performance problems with welded, steel moment-frame connections discovered following the 1994 Northridge earthquake. SEAOC is a professional organization composed of more than 3,000 practicing structural engineers in California. The volunteer efforts of SEAOC's members on various technical committees have been instrumental in the development of the earthquake design provisions contained in the *Uniform Building Code* and the 1997 *National Earthquake Hazards Reduction Program (NEHRP) Recommended Provisions for Seismic Regulations for New Buildings and other Structures*. ATC is a nonprofit corporation founded to develop structural engineering resources and applications to mitigate the effects of natural and other hazards on the built environment. Since its inception in the early 1970s, ATC has developed the technical basis for the current model national seismic design codes for buildings; the *de facto* national standard for postearthquake safety evaluation of buildings; nationally applicable guidelines and procedures for the identification, evaluation, and rehabilitation of seismically hazardous buildings; and other widely used procedures and data to improve structural engineering practice. CUREe is a nonprofit organization formed to promote and conduct research and educational activities related to earthquake hazard mitigation. CUREe's eight institutional members are the California Institute of Technology, Stanford University, the University of California at Berkeley, the University of California at Davis, the University of California at Irvine, the University of California at Los Angeles, the University of California at San Diego, and the University of Southern California. These laboratory, library, computer and faculty resources are among the most extensive in the United States. The SAC Joint Venture allows these three organizations to combine their extensive and unique resources, augmented by subcontractor universities and organizations from across the nation, into an integrated team of practitioners and researchers, uniquely qualified to solve problems related to the seismic performance of steel moment-frame buildings.

# ACKNOWLEDGEMENTS

Funding for Phases I and II of the SAC Steel Program to Reduce the Earthquake Hazards of Steel Moment-Frame Structures was principally provided by the Federal Emergency Management Agency, with ten percent of the Phase I program funded by the State of California, Office of Emergency Services. Substantial additional support, in the form of donated materials, services, and data has been provided by a number of individual consulting engineers, inspectors, researchers, fabricators, materials suppliers and industry groups. Special efforts have been made to maintain a liaison with the engineering profession, researchers, the steel industry, fabricators, code-writing organizations and model code groups, building officials, insurance and risk-management groups, and federal and state agencies active in earthquake hazard mitigation efforts. SAC wishes to acknowledge the support and participation of each of the above groups, organizations and individuals. In particular, we wish to acknowledge the contributions provided by the American Institute of Steel Construction, the Lincoln Electric Company, the National Institute of Standards and Technology, the National Science Foundation, and the Structural Shape Producers Council. SAC also takes this opportunity to acknowledge the efforts of the project participants – the managers, investigators, writers, and editorial and production staff – whose work has contributed to the development of these documents. Finally, SAC extends special acknowledgement to Mr. Michael Mahoney, FEMA Project Officer, and Dr. Robert Hanson, FEMA Technical Advisor, for their continued support and contribution to the success of this effort.

# PREFACE

The primary objectives of the FEMA/SAC Phase II Steel Project are to develop guidelines for the seismic evaluation, inspection, repair, design and construction of moment resisting steel frame buildings. A diverse collection of technical investigations is supporting this effort, including the identification of basic material properties in rolled steel sections; development of appropriate welding materials, details, and inspection procedures; specification of anticipated seismic demands imposed on connections as a result of structural response to strong ground motions; and large-scale connection testing to calibrate and verify the design procedures that are ultimately proposed. Tying these activities together is a series of detailed finite element analyses of various connection configurations to quantify the influence of material properties, geometry, and detailing on predicted behavior. In addition, a series of studies have been performed to incorporate the results of the various investigations into a performance based seismic engineering format that can become the basis of the SAC guidelines. Cost and risk studies and investigations into the past performance of this class of structures were also performed to gather valuable information used in the development of the guidelines and other documents.

This reports documents an analytical investigation into seismic performance of two buildings designed with partially restrained (PR) connections as the main elements in the lateral force resisting system. A three story and nine story building were designed for this analysis. The buildings were redesigns of buildings previously designed using fully restrained (FR) connections. Member sizes were taken as the same as in the FR design. Connection stiffnesses and capacities were varied over a range of values to investigate their influence on the response of the PR frames. Nonlinear time history analyses were performed on a suite of ground motions to compare the performance with the FR designs. Nonlinear static analyses were also performed. The analyses generally indicated that the performance was more sensitive to the capacity of the PR connections than the stiffness. As a result, the report recommends that PR moment connections be designed for at least half the expected strength of the connecting beam. This study indicates that buildings designed with PR connections may acceptable performance in regions subjected to high seismic demands. This work was performed at Lehigh University. This report comprises part of the work completed as part of Task 5.4.7 of the SAC Phase II Program.

Numerous individuals helped to develop the scope and content of the project and to review a preliminary version of this report. These individuals included members of the Technical Advisory Panel (TAP) for Systems Performance, selected members of the Connection Performance TAP; and several members of the Project Oversight Committee. The contributions of these individuals are greatly appreciated.

# OVERVIEW OF OBJECTIVES AND APPROACH

The objectives of the present study are to study the seismic performance of framing systems having partially-restrained (PR) bolted connections and to investigate feasibility of using the systems in different seismic zones of the United States. The PR connections are less stiff and weaker than the fully-restrained (FR) connections. However, they may not necessarily produce inferior structure as compared with the FR connections (Mayangarum and Kasai 1997). The study consists of two parts as follows:

Part 1: Design and Analysis of 3- and 9-Story PR Framing Systems.
Part 2: Effects of Connection Stiffness and Strength on Seismic Performance.

Part 1 is contained in a report "Seismic Performance of 3 and 9 Story PR Moment Frame Buildings" (Maison and Kasai 1998). The two study buildings are redesigns of the beams, columns, and connections of the SAC welded steel moment frame (WSMF) model buildings. The PR connections are used for both the exterior and interior frames of the building, in contrast to the SAC building having FR and simple connections in the exterior and interior frames, respectively. The building foot prints, column spacing, story heights, and live loads are the same as those for the SAC building.

Part 2 study is contained in this report. In contrast to Part 1, the present study considers connection modifications of the exterior frames of the SAC buildings, by retaining original beam and column sizes. The study highlights the effects of PR connection stiffness and strength on the buildings' dynamic properties and seismic performance. It considers PR modifications of all nine SAC welded steel moment frame (WSMF) models which have three different heights (3, 9, and 20 story) and are designed for three different seismic zones (Los Angels, Seattle, and Boston). The PR connections are assumed to have the following different bilinear PR properties.

3 different connection rotational stiffnesses
(low, medium, and high compared with the beam rotational stiffness).

3 different connection yield strengths
(one-third, two-third, and one times the beam plastic moment).

2 different post-yielding stiffnesses
(low and high).

Including the 9 original WSMFs, a total of 171 (= 9 + 9x3x3x2) framing systems are studied. Inelastic static push-over analyses and dynamic analyses are conducted. For each framing system 40 ground motions are used (20 motions for each of probabilities of 2% and 10% over 50 years). The results of 171 static analyses and 6,840 (=171x40) dynamic analyses are summarized.

# ACKNOWLEDGEMENT

This research is a part of Task 5.4, “System Performance” of the SAC Joint Venture Project. The writers are grateful to Task 5.4 team leader, Professor Helmut Krawinkler for excellent leadership and guidance for the team, as well as patience over the writer’s research progress.

The writers also appreciate valuable input from the Task 5.4 Advisory Panel as well as SAC Project Management Committee. Special thanks are given to Mr. James Malley for his generosity and patience.

The writers also acknowledge Mr. Kentaro Makishima, Mr. Michihiko Teramoto, and Mr. Kazuyuki Oohara, graduate students, Tokyo Institute of Technology, for their assistance in production of the figures and tables.

# TABLE OF CONTENTS