SAC
Steel Project

Background Document

Simplified Design Models for Predicting the Seismic Performance of Steel Moment Frame Connections

Report No. SAC/BD-00/15

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

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Submitted for distribution to
SAC Joint Venture
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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.

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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.

The primary responsibility of the Connection Performance team in the Phase II Steel Project is to develop straightforward and reliable design and analysis tools for seismic moment resisting connections in steel frame structures. This report provides an overview of the reasoning used to define the seismic performance of connections during the project. The report focuses on bolted flange plate, welded flange plate, extended end plate and T-stub connections. Past research is examined in detail and the behavior of various tests is documented. The various yield and failure modes of the different connections are evaluated and prioritized and put into a hierarchy. Comparison of the yield modes to the failure modes are made in order to understand the level of deformation ductility that can be achieved. It should be recognized there were significant opportunities for corroboration and expansion of the data generated from individual projects in developing a better understanding of the performance of moment connections as a whole. In other words, the whole of the investigations is greater than the sum of the parts. The results of all the studies in concert led to the development of design procedures for the various connections. These procedures were used in the development of the State of Art report on Connection Performance and in the design guidelines, though some differences occur in the final equations. This task was performed at the University of Washington and identified as Task 5.3.2 of the SAC Phase II program.

Numerous individuals helped to review the information provided in this report. These individuals included members of the Technical Advisory Panel (TAP) for Connection Performance, and several members of the Project Management Committee and the Project Oversight Committee. The contributions of these individuals are greatly appreciated.

Simplified Design Models for Predicting the Seismic Performance of Steel Moment Frame Connections

Summary

This report provides an overview of the reasoning used to define the seismic performance of connections during the SAC Phase 2 Research Program. The report focuses on bolted-flange-plate, welded-flange-plate, extended-end-plate, and T-stub connections. Past research is examined in detail and the behavior of each individual test is evaluated and tabulated. The seismic performance of connections depends upon the strength, stiffness and ductility of the connections. The yield mechanisms and failure modes are essential to establishing the strength and ductility of all connection types. The yield mechanism that controls connection ductility has the lowest resistance compared to all other yield mechanisms and all failure modes. This yield mechanism resistance predicts initiation of yielding. The critical failure mode has the lowest resistance of all other possible failure modes of the connection, and this resistance is also the maximum resistance expected in an experimental investigation. If the resistance of the controlling failure mode is significantly larger than one or more yield mechanism resistances, significant ductility and plastic rotation capacity are expected for the connection. If the resistance of the controlling failure mode is smaller or only slightly larger than the controlling yield mechanism, little or no ductility or plastic rotation capacity is expected.

Elementary mechanics models are developed to predict the resistance of each yield mechanism and each failure mode. The models are simple enough for use by practicing engineers to evaluate connection performance, but also accurate, since they must provide a reliable indication of the yield mechanism and failure modes that control the connection behavior. Different models are compared, and statistically evaluated to determine the model that best represents the connection performance. This procedure is applied for the four connection types, and equations for predicting the modes and mechanisms are presented. Plastic rotations are estimated as a function of the controlling yield mechanism and failure modes for each connection type. Statistical estimates of the accuracy of the individual equations are provided.

The methods and models from this study define the techniques used to establish yield mechanisms, failure modes, performance expectations and connection rotational capacity for all connection types. The analytical methods and many of the equations described in this report are used in the *Connection Performance State of Art Report*, which is published as FEMA Report 355D. However, there are also changes in some equations and predictions in that more comprehensive state of the art report, because additional experimental research was completed after the limits of this study were established.

Table of Contents