SAC
Steel Project

Background Document

Cyclic Testing of Bolted Moment End-Plate Connections

Report No. SAC/BD-00/21

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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Structural Engineering and Materials

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

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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 documents the results of an investigation of the seismic performance of extended end plate moment connections. The objectives of this program were to determine the suitability of the extended end plate connections for seismic moment frame applications, and to develop design procedures for this detail. The experimental program included eleven full scale connection tests. Four bolt extended unstiffened, eight bolt extended stiffened and four bolt wide extended unstiffened configurations were cyclically tested in this project. Specimen design addressed the behavior of both the strong plate (inelastic deformations predominantly in the beams) and weak plate (predominant inelastic action in the plate and bolts). One test was performed with a composite slab to determine the effects of the slab on the behavior on a four bolt extended unstiffened connection. An finite element analytical study was conducted to validate the experimental results and assist in the development of design procedrues. The results indicate that both the four bolt extended unstiffened and the eight bolt extended stiffened end plate connections can be designed and detailed for use in seimsic applications. The test results led to the recommendation that the four bolt wide extended unstiffened detail should not be used for seismic loading. The composite slab test demonstrated increased demand on the bottom flange connection bolts that should be considered in the connection design. This project was performed at Virginia Tech. This task was identified as Task 7.10 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 Connection Performance; selected members of the Joining and Inspection TAP; and several members of the Project Oversight Committee. The contributions of these individuals are greatly appreciated.

EXECUTIVE SUMMARY

This is the final test report for SAC Subtask 7.10 of Phase II of the SAC Steel Project. The objectives of the test program were to determine the suitability of the extended moment end-plate connections for use in seismic load resisting moment frames and to develop procedures for the design of the connections when subjected to seismic loads.

Eleven beam-to-column extended moment end-plate connection tests were performed. The four bolt extended unstiffened, eight bolt extended stiffened, and the four bolt wide extended unstiffened end-plate configurations were tested under cyclic loading in accordance with the *SAC Protocol* (SAC, 1997). For each test configuration, two different connection tests were performed. One test with the connection designed to develop 110 percent of the nominal plastic moment strength of the beam (strong plate connection). The other connection test was designed to develop 80 percent of the nominal plastic moment strength of the beam (weak plate connection). To investigate the effects of a composite slab on the behavior of the connection, one test was conducted using the four bolt extended unstiffened strong plate connection with a 5 in. composite slab. A validation study, utilizing the finite element method, was conducted to validate the experimental test results and to determine if the finite element method could be used to reliably predict the behavior of extended moment end-plate connections.

The results of the ten bare steel extended moment end-plate connection tests indicated that the four bolt extended unstiffened and eight bolt extended stiffened end-plate connections can be detailed and designed to be suitable for seismic loading. The four bolt wide extended unstiffened connection tests failed in a combination of end-plate tearing and bolt rupture. As a result of the unfavorable performance, the four bolt wide connection is not recommended for use in seismic force resisting frames until further analytical and experimental investigation are complete.

The results of the composite slab test indicated that the composite slab increases the demand on the bottom flange connection bolts, resulting in a brittle failure. As a result, the effects of the composite slab should be considered in the design of the connection.

ACKNOWLEDGEMENTS

Funding for this research was provided by the Federal Emergency Management Agency through the SAC Joint Venture. SAC is a partnership of the Structural Engineers Association of California, the Applied Technology Council, and California Universities for Research in Earthquake Engineering.

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