SAC
Steel Project

Background Document

Cover-Plate and Flange-Plate Reinforced Steel Moment-Resisting Connections

Report No. SAC/BD-00/27

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
Taejin Kim, Andrew S. Whittaker, Amir S. J. Gilani,
Vitelmo V. Bertero, and Shakhzod M. Takhirov
Pacific Earthquake Engineering Research Center, University of California, Berkeley

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

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DISCLAIMER

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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 experimental and analytical investigation of the seismic performance of welded cover plate and flange plate moment connections. This detail gained some widespread use in the time just after the Northridge earthquake as a means of reducing the demands on the welded connection. This study was performed to better understand the behavior of this class of connections. Various details and configurations were tested to understand the range of response. The experimental program included ten full scale connection tests. This report summarizes the results of the test program and compares the strength prediction to actual values obtained from the test results. The results of the tests and analyses were used in the development of a design procedure intended to result in ductile performance of this type of connection. This project was performed at the Earthquake Engineering Research Center at the University of California at Berkeley. This task was identified as Task 7.08 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.

ABSTRACT

Five cover-plate and five flange-plate-reinforced steel moment-resisting connections were studied by analysis and experimentation. All ten were single-sided steel beam-column assemblies that are representative of exterior beam-column connections, and all ten were composed of W14x176 Grade 50 columns and W30x99 Grade 50 beams. The reinforcing plates were fabricated from Grade 50 steel. A solid-element model of each connection was prepared and analyzed prior to the fabrication of the test specimens. Following completion of the testing program, solid-element and shell-element models of selected connections were prepared using measured material properties and were analyzed for the purpose of augmenting the experimental observations. None of the ten connections failed in a catastrophic manner; the strength of each connection degraded slowly due to local buckling of the beam web and flanges. The ten reinforced connections performed substantially better than the unreinforced connections of the SAC Phase I project and are technically viable alternatives to moment-resisting connections reinforced with haunches or connections utilizing reduced beam sections. The procedures of FEMA 267A can be used to design and detail connections reinforced with flat plates. Flange-plate connections are marginally less likely to suffer brittle or ductile fracture than cover-plate connections. Beam web connections should be groove welded to the column flange. Rectangular reinforcing plates are preferable to trapezoidal or swallow-tail shaped plates. Reinforcing plates should be joined to beam flanges using three-sided fillet welds. Bracing of the beam bottom flange outside the plastic hinge zone will not produce significant improvements in connection hysteresis. It is impractical to share large plastic rotations between a panel zone and a beam cross section across a wide range of story drifts. The effectiveness of beam web reinforcement in the form of plates welded to the beam web and the column flange is likely most limited. The use of overly thick reinforcing plates in either cover- or flange-plate connections is discouraged.

ACKNOWLEDGMENTS

The work described in this report was funded by the SAC Joint Venture through a contract with the Pacific Earthquake Engineering Research (PEER) Center. This financial support is gratefully acknowledged.

Rolled steel sections were supplied at no cost to the University by Nucor Yamato, Inc, of Blytheville, Arkansas. The ten test specimens were fabricated and shipped to the University at no cost by Gayle Manufacturing Company, Woodland, California. Fabrication inspection services and testing services were provided by Signet Testing Laboratories, Inc. of Hayward, California to the University at no cost. The research described in this report could not have been undertaken without this generous support.

Many individuals made significant contributions to this research program. Special thanks are due to Mr. Rick Wilkinson of the Gayle Manufacturing Company, Mr. Michael Engestom of Nucor Yamato, Inc.; Mr. Robert Tongson of Signet Testing Services; Messrs. Don Clyde and Wesley Neighbour and Ms. Janine Hannel of PEER; Mr. Jim Malley of Degenkolb Engineers; Mr. Ron Hamburger of EQE International; Professor Stephen Mahin of the University of California, Berkeley; Professor Helmut Krawinkler of Stanford University; Professor Charles Roeder of the University of Washington; and Professor Chia-Ming Uang of the University of California, San Diego.

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