**SAC**
***Steel Project***

***Background Document***

# Development and Evaluation of Improved Details for Ductile Welded Unreinforced Flange Connections

## Report No. SAC/BD-00/24


**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
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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 a combined experimental and analytical investigation on improving the performance of unreinforced moment connections for use in seismic resistant construction. Issues such as the geometry and size of the access holes, the amount of panel zone deformation, the use of supplemental web fillet welds, the influence of continuity plates, and the effects of concrete slabs were all studied as part of the investigation. The experimental work included six exterior and five interior full scale cyclic connection tests. In addition, this project included detailed nonlinear finite element studies of unreinforced connections subjected to both monotonic and cyclic loading. A low cycle fatigue formulation was developed to evaluate the cyclic ductility of various configurations. The tests and analytical work indicate that unreinforced connections can provide ductility. A recommended design procedure was developed for this class of connections. This project was performed at Lehigh University. This task was identified as part of Task 7.05 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

The research presented in this report focused on improving the cyclic inelastic performance of welded unreinforced flange moment connections. Both analytical and experimental studies were conducted to investigate the effects of five issues on the cyclic ductility of welded moment connections. These issues included: (1) geometry and size of the weld access holes, (2) control of inelastic panel zone deformation, (3) supplemental web fillet welds, (4) continuity plates, and (5) the effects of a concrete slab.

The experimental studies consisted of inelastic cyclic tests of full-scale connection specimens. The test program included six exterior connection specimens and five interior connection specimens. The analytical studies included nonlinear finite element analysis of connections subjected to monotonic and cyclic loading. A low-cycle fatigue failure formulation was developed and applied to analytically evaluate the cyclic ductility of various connection details.

The results of the study indicate that the type of connection fracture observed after the Northridge earthquake is primarily due to the low toughness of the weld metal used in making the flange welds. With a high toughness weld metal and modified detailing improvements, it is demonstrated that a welded unreinforced flange moment connection can reliably achieve an inelastic rotation of 0.03 radian or more prior to beam fracture. Based on the analytical and experimental results of the study a design procedure with modified details for welded unreinforced moment connections is presented. The modified details include using a groove welded beam web attachment with supplemental fillet welds along the edges of the shear tab. An alternative detail consisting of a heavy shear tab that is shop groove welded to the column and fillet welded to the beam web in the field also was found to be successful. The modified detail also includes the use of a weld access hole with a modified geometry. The tests and analysis results both indicate that a strong panel zone enhances inelastic connection performance. Existing seismic design criteria which requires continuity plates in all moment connections was found to be conservative, and could probably be relaxed. A proposed continuity plate design criteria based on low-cycle fatigue failure was developed that shows good correlation with the test results.

The low-cycle fatigue failure analysis procedure is demonstrated to reliably locate the regions in a connection where high fracture potential exists as well as to predict the cyclic ductility.

# ACKNOWLEDGMENTS

Funding for this research was provided by grants from the Federal Emergency Management Agency through the SAC Joint Venture and the Department of Community and Economic Development of the Commonwealth of Pennsylvania through the Pennsylvania Infrastructure Technology Alliance (PITA). SAC is a partnership of the Structural Engineers Association of California, the Applied Technology Council, and California Universities for Research in Earthquake Engineering. This research was conducted as Task 7.05 under Phase II of the SAC Joint Venture.

Mr. James O. Malley is the Project Director of Topical Investigations for the SAC Joint Venture. PITA is co-directed by Dr. Pradeep Khosla and Dr. John Fisher.

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