SAC
Steel Project

Background Document

Tests on Bolted Connections
Part II: Appendices

Report No. SAC/BD-00/04A

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
James Swanson, Roberto Leon, and Jeffrey Smallidge
Georgia Institute of Technology, School of Civil and Environmental Engineering
Structural Engineering, Engineering Mechanics and Materials

Submitted for distribution to
SAC Joint Venture
650-595-1542
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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 investigation of the seismic performance of all bolted flange plate moment connections. The experimental program included 8 six full scale connection tests. This series of tests attempted o investigate two modes of ductile behavior: hinging of the girder and hinging within the flange plates. The tests demonstrated that both yielding mechanisms could produce stable hysteretic behavior. Net section tearing near the end of the bolted flange plate after substantial inelastic deformation was the ultimate failure mode for some of the early specimens in the test series. Subsequent tests included a clamp plate that improved the ductility of the joint. The results of this series of tests was used in the development of a design procedure intended to result in ductile performance of this type of connections. This report summarizes the results of the test program and compares the strength prediction to actual values obtained from the test results. The components and connections were evaluated for strength, stiffness and ductility. This project was performed at the Georgia Institute of Technology. This task was identified as Task 7.03 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 report provides a summmary of the work conducted under SAC task 7.03 - tests on Bolted Connections. It includes the results of 48 component T-stub tests and 10 component clip angle tests and 6 full-scale tests. The components and connections were evaluated based on their strength, stiffness and ductility characteristics. The results are used to compare several existing strength models that govern the failure modes of tension bolt fracture including prying forces, net section stem fracture, shear bolt fracture and block shear failure.

A monotonic stiffness model is developed based on the experimental observations and the results of an advanced finite element investigation. The stiffness model, which is based on a component spring model similar to that used in the Eurocode, includes stiffness contributions from a flange and tension bolt mechanism, stem deformation, and slip and bearing deformation. The flange/tension bolt stiffness model includes a variable tension bolt stiffness and various stiffnesses of the flange as it passes from a totally elastic state to a plastic mechanism. The slip and bearing deformation model includes the effects of initial shear bolt alignment and lack of fit. Because the stiffness model is based on rational mechanisms, it is able to predict the deformation at failure of a T-stub with reasonable accuracy.

Finally, modifications to existing strength models are recommended and a deterministic T-stub design procedure is presented that yields ductile beam-column connections.

It was found that (1) the most desirable behavior was obtained from T-stubs that were proportioned such that a flange mechanism and stem yielding developed simultaneously, (2) little difference in overall behavior was noted between components using A325 and A490 bolts, (3) a modified version of the strength model proposed by Kulak, Fisher, and Struik (1987) was found to provide reliable predictions of the T-stub flange capacity including the effects of prying, and (4) the block shear model proposed by Hardash and Bjorhovde (1985) was predicted a failure mechanism remarkably similar to that observed and provided a reasonable prediction of the capacity.

ACKNOWLEDGEMENTS

This research project was funded primarily by SAC - the Structural Engineers Association of California, the Applied Technology Council, and the California Universities for Research in Earthquake Engineering. Their support, both financial and technical, is gratefully acknowledged. The financial support of the Nucor-Yamato Steel Company, the LeJeune Bolt Company, and Cives Steel is also gratefully acknowledged.

Support for much of the model development was provided by a grant from the Mid-America Earthquake Center.

This project would not have been possible without the assistance of several people, including Brian B. Edenfield, William Peltier, and Frank "Comer" Lyons, and Daniel Kokan. Their contributions are gratefully acknowledged.

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