SAC
Steel Project

Background Document

Strength and Ductility of FR Welded-Bolted Connections

Report No. SAC/BD-98/01

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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April 15, 1998

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 now underway 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.

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 moment resisting connections in steel frame structures. This report presents the results of a pilot study to determine the suitability of incorporating fracture mechanics theory in finite element studies of steel moment frame connections. Both two-dimensional and three-dimensional analyses of actual specimens tested in the Phase 1 project have been modeled in detail, and in general the simulations are shown to predict the observed behavior within certain limitations. The influence of several different types of details on fracture behavior is identified, such as weld backing bars (with and without reinforcing fillets) and cover plates. Significant effort is also devoted to quantifying the effects of weld material properties (toughness and strength), initial weld flaws, and modeling assumptions on crack initiation and propagation.

At the time of this writing, there is a second series of studies underway that is employing plasticity-based finite element models to predict the behavior of steel moment connections. These studies share an approach similar to those presented in this report, in that the baseline analyses are focused on reproducing the behavior of actual test specimens, providing confidence in extending the models to different material properties, geometries, and details. A final program of finite element investigations is now being planned to synthesize the results of the first two investigations with the results of materials, welding, and large-scale connection tests in the Phase II project.

Numerous individuals helped to review a preliminary version of this report, including members of the Technical Advisory Panel (TAP) for Connection Performance; selected members of the Materials and Fracture, and Joining and Inspection TAPs; and several members of the Project Oversight Committee. The contributions of all of these individuals are greatly appreciated.

SUMMARY

The objectives of this project are: 1) to develop a more thorough understanding of the inelastic behavior of pre-Northridge fully restrained welded-bolted connections, and 2) to lay the groundwork for the development of connection details that are not fracture critical. These objectives are addressed through detailed three-dimensional nonlinear finite element analyses of connection subassemblages. The studies reported do not account for fracture propagation. They are concerned with the potential for cracking only through the development of stress states or material conditions that would facilitate fracture if a flaw or other irregularity were introduced.

The characteristics of the analysis configurations utilized in this research are derived from the geometry of Berkeley specimen PN3, which consists of a W36x150 beam connected to W14x257 column. By changing some of the attributes of specimen PN3, different analysis configurations are created. Important geometric and material parameters are varied over the practical range of interest in order to evaluate their effect on behavior. To compare between the behavior of the different configurations analyzed in this research, and to assess the effect of the parameters of interest, a number of different stress, strain, and combined stress/strain indices are employed. These quantities are sampled at connection plastic rotations ranging from 0.0025 to 0.03 *rad*.

The following is a summary of important results concluded from the nonlinear finite element analyses conducted as part of this research:

- Stress triaxiality and plastic strains computed from the finite element analyses suggest that observed brittle fractures at the weld-column interface probably occurred due to large pre-existing flaws at the interface rather than limited ductility caused by large hydrostatic stresses. Stringent quality control is therefore key to improved connection performance.

- The finite element analyses show that the behavior of the analyzed connections is insensitive to steels with yield-to-ultimate stress ratios (f_y/f_u) less than 0.8 for connection plastic rotations up to 0.03. The analyses further show that steel with a high yield-to-ultimate stress ratio ($f_y/f_u = 0.95$, for example) can result in a large reduction in the plastic hinge length of the beam, which leads to significantly greater local strains and earlier local buckling.

- Results from the finite element analyses suggest that enlarging the size of the access hole to facilitate welding could significantly increase the potential for ductile fracture at the root of the access hole.

- The finite element analyses support the FEMA-267 (1995) recommendations, which require the use of continuity plates in all connections. However, the analyses also suggest that the provisions may be relaxed with regards to required continuity plate thickness for one-sided connections such as those considered in this research.

- Comparisons between finite element results and currently recommended provisions show that panel zone strength provisions are reasonable for interior connections, but need to be modified for one-sided (exterior) connections.

This research provides extensive information on the effect of influential design variables on inelastic behavior and potential for fracture of welded-bolted connections. Further research is needed to utilize this information, as well as results from other published analytical and experimental studies, to develop more comprehensive criteria for the design of fracture-resistant connections. Finally, much research is still needed to tie results from local analyses of the sort presented in this report to global frame behavior.

ACKNOWLEDGEMENTS

This is the final report for Sub-Task 5.3.1(b) of Phase II of the SAC Steel Project (CUREe/SAC, Subcontract No. II-36) conducted under the direction of James O. Malley, Project Director for Topical Investigations, and Charles Roeder, Team Leader for Topical Studies on Connection Performance. The SAC Joint Venture is a partnership of the Structural Engineering Association of California (SEAOC), the Applied Technology Council (ATC), and the California Universities for Earthquake Engineering (CUREe). The work forming the basis for this publication was conducted pursuant to a contract with the Federal Emergency Management Agency (FEMA). The substance of such work is dedicated to the public. The authors are solely responsible for the accuracy of the statements or interpretations contained in this publication. No warranty is offered with regards to the results, findings, and recommendations contained herein, either by FEMA, the SAC Joint Venture, the individual joint venture partners, their directors, members or employees. These organizations and individuals do not assume any legal liability or responsibility for the accuracy, completeness, or usefulness of any of the information, product or processes included in this publication.

The authors gratefully acknowledge the suggestions and review comments received from the following individuals: James Malley, Charles Roeder, Steve Mahin, Robert Dodds, Stanley Rolfe, Roger Ferch, Gregory Deierlein, Wei-Ming Chi, Donald White, and Bill Mohr.

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