SAC
Steel Project

Background Document

Integrative Analytical Investigations on the Fracture Behavior of Welded Moment Resisting Connections

Report No. SAC/BD-99/15

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
Gregory G. Deierlein and Wei-Ming Chi
John A. Blume Earthquake Engineering Center
Department of Civil & Environmental Engineering
Stanford, University

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

July 5, 2000

DISCLAIMER

SAC

Steel Project

Background Document

Integrative Analytical Investigations on the Fracture Behavior of Welded Moment Resisting Connections

Report No. SAC/BD-99/15

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
Gregory G. Deierlein and Wei-Ming Chi
John A. Blume Earthquake Engineering Center
Department of Civil & Environmental Engineering
Stanford, University

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

July 5, 2000

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.

This report was carried out as part of the overall efforts in the Phase II Steel Project to understand the interrelation among factors that influence the behavior of welded steel beam to column connections. In particular, this effort was undertaken to bridge between other Phase II efforts related to classical fracture mechanics predictions of behavior, detailed ductile or brittle finite element idealizations of connection behavior, tests of materials and weldments, and tests of complete beam to column assemblies. In this investigation, a series of consistent analyses were undertaken to synthesize, assess and information obtained from these other Phase II investigations. In many cases, specific examples were selected to assist directly in the development of design guidelines. This work was conducted at Stanford University. This project was identified as Task 5.3.3 in the FEMA/SAC Phase II work plan.

Numerous individuals helped to develop the scope and content of this project and to review a preliminary version of this report. These individuals included the members of the Technical Advisory Panels for Connection Performance, Materials and Fracture, and Welding and Inspection as well as the Project Management Committee and several members of the Project Oversight Committee. The contributions of these individuals are greatly appreciated.

ACKNOWLEDGMENTS

This is the final project report for Task 5.3.3 of Phase II of the SAC Steel Project (Subcontract Agreement No: 2TA5.3.3 – 01 and 2TA5.3.3 – 02), conducted under the direction of James 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 Engineers Association of California, the Applied Technology Council, and the California Universities for Research in Earthquake Engineering. The work forming the basis for this publication was conducted pursuant to a contract with the Federal Emergency Management Agency (FEMA). The authors are solely responsible for the accuracy of statements or interpretations contained in this publication. No warranty is offered with regard to the results, findings and recommendations contained herein, either by the 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 information, helpful suggestions and review comments received from the following individuals over the course of the project: Robert Dodds, Anthony Ingraffea, Steve Mahin, James Malley, Tina Panontin, Robert Dexter, Karl Frank, James Ricles, Matt Johnson, Stanley Rolfe, John Barsom, John Fisher, and Duane Miller.

EXECUTIVE SUMMARY

The objective of this investigation is to utilize finite element analyses to investigate the fracture behavior of welded beam-column connections and, thereby, examine how fracture resistance is influenced by various design and detailing parameters. A related objective is to help integrate fracture-related data from other SAC investigations on materials, welding/joining and connection testing. The ultimate goal is to provide behavioral information to guide the development of guidelines and acceptance criteria for the design of fracture resistant welded beam-column connections.

This study is a follow-up to a preliminary investigation by the authors, conducted under SAC Subtask 5.3.1, to examine "pre-Northridge" style connections tested during Phase I of SAC. The present investigation extends the earlier study to address a broader range of design and detailing parameters and fracture effects. Elastic and inelastic finite element fracture analyses are used to evaluate fracture toughness demands in terms of mode I stress intensity factor (K_I) and Crack Tip Opening Displacement (CTOD). In addition, advanced analyses that employ a micro-mechanical fracture criterion (Stress Modified Critical Strain) are used to examine ductile crack initiation in locations without an initial flaw. Computed fracture demands are evaluated in light of test data from relevant material, weldment and connection tests. Parameters investigated include the following:

- weld flaw locations
- built-up welds with filleted reinforcement
- variations in beam and column sizes
- relative strength of beam to joint panel zone
- influence of continuity plates
- significance of welding-induced residual stresses
- influence of weld access hole geometry
- connections with Reduced Beam Sections (RBS)
- through-thickness fractures in column flanges

Data from the analyses substantiate observations from connection tests which indicate that improved weld details and higher toughness materials alone are not sufficient to reliably provide the inelastic deformation capacity required for seismic design. Standard, i.e., "pre-Northridge" style, connections made with notch toughness rated weld and base metals (CVN > 40 to 50 ft-lbs at 70°F) and small initial flaws ($a_o < 0.1$ inch) are shown capable of reliably achieving their full plastic strength, but toughness demands required to sustain larger inelastic hinge rotations generally exceed the toughness of common notch tough weld metals. On the other hand, the analyses do confirm the effectiveness of improved connections, such as the Reduced Beam Section (RBS) detail, to limit toughness demands within attainable limits. Analyses of RBS connections indicate that control of panel zone deformations is essential to limit fracture toughness demands in the critical beam flange weld. The sensitivity of fracture toughness demands to panel zone strength, and consequently panel zone deformations, is also apparent in standard (non-RBS) details. Other general observations and conclusions from the analyses include the following:

- Weld yield strength overmatching that is generally achieved with E70 weld metal and A572 Gr. 50 base metal (based on their average yield strengths of F_{yw} = 65 ksi and F_{yb} = 55 ksi, respectively) is beneficial for reducing toughness demands at weld root flaws at the weld-to-column interface. However, overmatching does not offer much if any such benefit for flaws at the weld-to-beam flange interface.

- Fracture toughness demands caused by the gap behind the backing bar are shown to be insensitive to the backing bar thickness or the fusion length between the backing bar and weld. Fillet welds used to seal the backing bar gap can reduce toughness demands at the built-in crack tip, however, their effectiveness depends on there being a sufficient fusion length between the backing bar and the groove weld to transfer stress into the seal weld.

- Inelastic toughness demands for flaws located at the weld-to-beam interface are generally about twice that of flaws at the weld-to-column interface (weld root). This suggests that more stringent acceptance criteria are appropriate for flaws at the weld-to-beam interface, particularly for weld toe cracks in the top-flange. Additionally, flaws on the inside faces of the beam flanges (the top of the bottom flange and bottom of the top flange) have much smaller toughness demands than flaws on the outside faces (the extreme fiber locations). This helps to explain the prevalence of bottom flange, versus top flange, fractures when weld backing bars are left in place.

- Welding-induced residual stresses appear to be most significant at low stress levels where the behavior is elastic. In such cases, analyses indicate that the residual stresses impose an inherent toughness demand of about $K_I \approx 20$ ksi$\sqrt{\text{in}}$ at the weld root flaw. At larger inelastic deformations the change in toughness demand due to residual stresses becomes less significant, relative to other factors, due to large-scale yielding.

- Analyses of a connection with a W14 x 550 column indicate that when the column flanges are sufficiently thick (in this case, t_{fc} = 3.82 inch), the presence of continuity plates does not have a significant effect on fracture toughness demands at the beam flange weld. However, for columns with thinner flanges the presence of continuity plates can significantly reduce the toughness demand. For example, in a connection with a W21 x 131 column (t_{fc} = 0.96 inch), the addition of continuity plates decreases the maximum toughness demand by roughly 60% relative to the case without continuity plates.

- Analyses of connections with different size beams and columns indicate that toughness demand is most sensitive to the column flange thickness and the joint panel zone strength. Even when continuity plates are present, the fracture toughness demand at the weld root increases with decreasing flange thickness, implying that toughness demands are generally larger for deep column members with thin flanges as compared to shallower heavier columns with thick flanges. Beyond this, the toughness demand also increases with increasing shear deformation of the joint panel zone.

- Comparative analyses between the SAC Task 5.12 through-thickness pull-plate test specimens and beam-column connections confirm that critical stress and strain conditions generated in the pull-plates exceed those in the beam-column connections. This indicates that, insofar as the materials in the pull-plate tests match those used in practice, through thickness column fractures are unlikely to occur in welded beam-column connections.

- Comparative analyses of SAC Task 7.05 T-stub weldment tests and beam-column connections show that the stress/strain states and fracture demands in the two can vary considerably. Thus, results from the T-stub tests are not directly transferable to beam-column connections. However, when interpreted through analytical fracture analyses, results from the T-stub tests can be used to establish the insitu fracture toughness of groove welds and the influence of welding materials and procedures on toughness.

This page is intentionally left blank

CONTENTS