**SAC**
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# Finite Element Fracture Mechanics Investigation of Welded Beam-Column Connections

## Report No. SAC/BD-97/05

**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
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Submitted for distribution to
**SAC Joint Venture**
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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 purpose of this investigation is to examine methods to quantify fracture toughness demands in seismically designed welded beam-to-column connections. Detailed finite element models of beam-column subassemblies are used to calculate elastic stress intensity factors ($K_I$) and inelastic Crack Tip Opening Displacements (CTOD) at backing bar gaps and root defects in beam flange welds. These indices can be used to evaluate fracture sensitive connections and to determine material toughness requirements to prevent premature fractures. Therefore, the analyses offer insights for both evaluation of existing conditions and development of improved fracture-resistant designs.

The overall goals and scope of the project are to:

- Evaluate the effectiveness of 2-D and 3-D finite-element fracture analyses to predict cracking observed in connection tests conducted during Phase I of the SAC project.
- More completely understand fracture behavior as influenced by connection details, internal stresses and strains, flaw sizes and locations, material strength and toughness.
- Provide the groundwork for developing a fracture mechanics based methodology to assess the likelihood of connection fracture in new and existing construction.

The investigation is developed around analyses of full-scale connection subassemblies that were tested at the University of Texas and the University of California at Berkeley during Phase I of the SAC Joint Venture. These connections were designed and fabricated in conformance with the 1991 Uniform Building Code following design and construction practice in effect prior to the Northridge earthquake. These specimens all failed due to brittle fractures and provide a reliable source of data on what are termed "pre-Northridge" connections. Also analyzed is another connection detail that has the same basic geometry as the "pre-Northridge" tests but with reinforcing flange cover plates designed and fabricated according to the SAC Interim Guidelines. In addition to the cover plates, this connection included other "post-Northridge" improvements, e.g., high toughness welding electrodes and removal/reinforcement of weld backing bars, which resulted in satisfactory behavior.

The investigation includes several different levels of fracture analyses that provide the following types of information:

1. *Elastic fracture initiation* analyses provide data to predict the onset of brittle fracture in connections with low-toughness materials and/or large flaws where linear elastic fracture mechanics is valid. Using failure loads and flaw size data from the "pre-Northridge" connection tests, elastic analyses showed consistent values of $K_{Ic}$ = 65 ksi$\sqrt{\text{in}}$ as the insitu toughness of welds made with E70-T4 electodes. The results agree with the observed failures and weld toughness data reported in other studies. The elastic analyses also provide information on the sensitivity of brittle fracture to factors such as flaw size, flaw location, and detailing features such as weld backing bars, flange cover plates, etc.

2. *Inelastic fracture initiation* analyses permit the extension of linear elastic fracture mechanics to consider cases with significant yielding and the effects of yielding on the fracture behavior. For example, these analyses provide data to suggest that the relative yield strengths of weld-metal to base-metal is significant, and that the use of overmatching electrodes could reduce fracture toughness demands in connections. Since they are valid over a larger range of behavior, the inelastic analyses provide information that is applicable to "post-Northridge" connection details with higher toughness electrodes where one expects significant yielding prior to fracture.

3. *Elastic and inelastic fracture propagation* analyses provide an indication of the sensitivity of crack trajectories to various design and loading parameters. The elastic analyses, for example, show that rather modest changes in the crack locations, column stresses, and geometry can dramatically change the crack trajectories. These data suggest that many of the observed column fractures can be explained by local phenomena within the connections rather than global effects such as column tension forces induced by vertical ground motions. Inelastic propagation analyses indicate that differences in failure loads caused by ductile crack extension are minimal, such that one can assume crack initiation as a reasonable measure of failure.

4. Comparison of results between two- and three-dimensional analyses indicate that variations of stresses and strains across the flange width significantly affect the calculated fracture indices, $K_I$ and CTOD. Moreover, these variations are largest for inelastic fracture indices (CTOD) calculated at the onset of yielding. Therefore, while two-dimensional analyses may be an effective tool for multi-parameter sensitivity studies, they should always be accompanied by three-dimensional analyses to account for shear lag and other distortional effects on the behavior.

5. Effectiveness of proposed improvements such as addition of flange cover plates or fillet weld reinforcement beneath backing bars are shown to depend on localized factors that may not be obvious from overall behavior. Analyses of the cover-plate connections, for example, indicate that the observed improvements may be more due to improved welding procedures and details than addition of the cover plates. The cover plates can, in fact, lead to unforeseen problems through the introduction of large horizontal cracks (caused by gaps between the plates and beam flanges) and an increase in the overall moment delivered to the column face.

Overall, this investigation confirms the usefulness of detailed finite element analyses for studying localized effects that influence fracture in the connections. It is recommended that further analyses be conducted to develop more comprehensive design guidelines, recommendations, and simplified fracture analysis models that can be used in both the evaluation/rehabilitation of existing structures and the design of new structures.

# ACKNOWLEDGMENTS

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## Contents