SAC
Steel Project

Background Document

Behavior and Design of Radius Cut Reduced Beam Section Connections

Report No. SAC/BD-00/17

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
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 a combined experimental and analytical investigation on radius cut reduced beam section (RBS) moment connections for use in seismic resistant construction. The investigation commenced with the compilation and assessment of previous RBS testing and design procedures. This led to the identification of three major issues to be studied in the full scale test program: the effect of a composite floor slab on RBS connection performance, the effect of large inelastic deformation of the joint panel zone, and the acceptability of a bolted web connection detail in lieu of a fully welded web connection. Eight full scale tests were performed at the University of Texas at Austin and Texas A&M University. In addition, this project included detailed finite element studies of RBS connections. The results of the FEMA work closely matched the experimental results, and demonstrated that a primary benefit of the RBS is to significantly reduce the inelastic strain demand at critical locations near the flange groove welds. This task was identified as Task 7.06 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.

SUMMARY

This report documents the results of a combined experimental and analytical study on radius cut reduced beam section (RBS) moment connections for use in seismic resistant steel moment frames. This study was conducted as part of the SAC Phase 2 Program, and was identified as SAC Task 7.06a.

Prior to this project, a significant experimental database was already available on the behavior of RBS moment connections. Past tests have shown that the radius cut RBS connection can provide excellent performance, sustaining large levels of deformation under cyclic loading on a consistent and reliable basis. Design procedures for RBS connections have also already been developed and previously published.

The primary purpose of this project was to evaluate selected aspects of RBS behavior that have not been adequately examined in previous testing, and to evaluate the suitability of available design procedures for RBS connections. Three major issues were investigated in these tests: the effect of a composite concrete floor slab on RBS connection performance; the effect of large inelastic deformations in the column panel zone on RBS connection performance; and the acceptability of a bolted beam web connection in lieu of a fully welded web connection.

A total of eight large-scale specimens were tested in this project. Each specimen was an interior type subassemblage, with beams attached to each flange of a column. Four of the specimens were bare-steel, whereas the other four were provided with a composite concrete floor slab. The specimens were constructed in pairs, where one specimen was bare steel and the other was composite. For each specimen of such a pair, the specimens were identical, except for the presence or absence of the composite floor slab. The first pair of specimens incorporated a bolted web connection detail and was designed so that yielding would occur in the RBS segments as well in the column panel zone. The second pair of specimens was similar to the first, except that a welded beam web connection was used rather than a bolted web connection detail. The third pair of specimens incorporated a bolted web connection detail combined with a very weak panel zone designed to be the dominant source of inelastic rotation. The fourth and final pair of specimens incorporated a bolted web detail combined with a very strong panel zone designed to remain elastic. All eight specimens used the same details and the same welding procedures for the beam flange groove welds. All beam flange groove welds were made with the self-shielded flux core arc welding process with a 3/32-inch diameter E70T-6 electrode.

Key results of the experimental program can be summarized as follows:

- The test specimens exhibited good performance overall. No fractures occurred at story drift angles less than 0.04 rad. The results of these tests add to a substantial database of successful radius cut RBS tests, and indicate that the radius cut RBS connection can reliably accommodate large drift angles without fracture.

- Sizing of the RBS cuts for these specimens (distance from face of column to start of cut, length of cut, and depth of cut) was based on previous published recommendations. These recommendations appear to provide a reasonable basis for sizing radius RBS cuts.

- The presence of a composite floor slab did not appear to promote early fracture or lead to other detrimental effects. To the contrary, the presence of the slab was beneficial to specimen performance by enhancing beam stability and delaying strength degradation. Based on these tests, it appears that no special treatment is needed for the slab, such as leaving a gap between the slab and the face of the column. No shear studs were placed within the RBS regions of the test specimens, to avoid the potential of beam flange fracture initiation at a stud weld. Leaving shear studs out of the RBS region appears to be a prudent precaution.

- Satisfactory performance was obtained for specimens with either bolted or welded web connections. Specimens with both types of web connections achieved at least 0.04 rad story drift without the occurrence of fracture. However, beyond this level of story drift, a connection with a bolted beam web connection experienced a base metal fracture adjacent to a beam flange groove weld, whereas no such fractures were observed in specimens with welded web connections. This is in line with past RBS tests with bolted webs, which have generally developed satisfactory story drift angles, but show a significantly higher incidence of fractures at higher drift levels as compared to specimens with welded web connections. Thus, while satisfactory performance is possible with a bolted web connection, it appears that a welded web is beneficial in reducing the vulnerability of RBS connections to beam flange fractures.

- None of the specimens tested in this program was provided with a supplemental lateral brace at the RBS. In fact, the unbraced length of the test specimen beams was approximately 35 percent beyond that permitted by current seismic codes for special moment frame beams. Despite this rather large unbraced length, and despite the absence of a lateral brace at the RBS, the specimens were still capable of maintaining 80% of their peak strength at 0.04 rad story drift angle. Thus, it appears that satisfactory performance is possible without a supplemental lateral brace at the RBS, and with lateral support spacing beyond that permitted by current codes.

- The test results suggest that the RBS segment of the beam may be prone to earlier web buckling, as compared to beams without an RBS. More stringent web slenderness limits may be justified for beams with reduced sections, as suggested by other researchers.

- Two specimens were tested with very weak panel zones. Essentially all yielding occurred within the panel zones of these specimens, with the RBS segments of the beams remaining essentially elastic. These specimens showed excellent performance, developing large story drift angles without strength degradation and exhibiting excellent energy dissipation. However, the connections of these specimens ultimately failed by beam flange fractures adjacent to groove welds, albeit at large drift levels. These fractures were apparently caused by high local demands in the weld region resulting from panel zone shear deformations.

Nonetheless, these specimens demonstrated that excellent performance is possible with very weak panel zones.

- No fractures occurred within the beam flange groove welds of any connection tested in this program. Thus, the E70T-6 SS-FCAW electrode, combined with the welding procedures, quality control measures, and backing bar and weld tab treatments used in this test program resulted in satisfactory weld performance. It should be noted, however, that these specimens were welded under ideal laboratory conditions, with close attention to quality.

In addition to the experimental program, this project also included finite element studies of RBS connections. Finite element models were developed for several test specimens. These included global models of entire specimens as well as local models of the region near the groove welds. Models were developed both with and without RBS cuts to better understand the role of the RBS cuts in connection performance. The overall load-deformation response of the global finite element models matched the experimentally measured responses quite closely, indicating that finite element analysis can reasonably predict connection response in the inelastic range. The local finite element models suggest that a primary benefit of the RBS cuts is to significantly reduce inelastic strain demand at critical locations near the beam flange groove welds. Further results of the finite element analyses are described in this report.

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