SAC
Steel Project

Background Document

Cyclic Response of RBS Moment Connections: Weak-Axis Configuration and Deep Column Effects

Report No. SAC/BD-00/23

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 an experimental and analytical investigation of the effect of column depth and orientation on the performance of welded web Reduced Beam Section (RBS) moment connections. Five full-scale specimens were tested, two with connections of an RBS beam to the weak-axis of a column and three with deep columns oriented in the strong axis direction. Both of the weak axis specimens exceeded 0.03 radians of plastic rotation and avoided brittle fracture of the beam flange groove welds. Complementary finite element analyses were performed to better understand the behavior of weak axis moment connections. Variations in the configuration of the flange continuity plates were examined to determine their effects on the local strain demands. Based on these tests and analyses, a design procedure for weak-axis RBS moment connections were developed. Two of the three deep column specimens were able to reach 0.03 radians of plastic rotation without experiencing brittle fracture in the welded joints. The third specimen experienced a brittle fracture along the k-area of the column just prior to reaching 0.03 radians of plastic rotation. All of the deep columns experienced undesirable column twisting. Analyses of this twisting indicated that high warping stresses occurred in the deeper columns. A procedure was developed to control these stresses. This task was identified as part of Task 7.11 of the SAC Phase II program. The testing was performed at the University of California at San Diego.

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.

ABSTRACT

This research was concerned with the performance of steel moment frame connections under simulated seismic loading conditions. A total of five full-scale, welded beam web moment connections, utilizing the reduced beam section design, were statically tested. Two of the specimens involved connections to the weak-axis of the column. The other three specimens were strong-axis connections with deeper column sections.

Neither of the weak-axis connections experienced brittle fracture or even large stress concentrations near the beam flange groove welds. Both specimens were able to reach the required 0.03 radian of plastic rotation. A series of parametric studies was carried out, using a finite element analysis program, to better understand the behavior of weak-axis RBS moment connections. It was found that the RBS was able to reduce the strain concentration at the edge of the beam flange near the groove weld by a factor of at least 2.6 for both specimens. The presence of far-side continuity plates allows the beam flange force to flow straight through the connection instead of towards the stiffer column flanges; far-side continuity plates, however, play an insignificant role in the reduction of stress concentrations at the beam flange groove weld. By varying the length that the continuity plate was allowed to stick out past the column face, it was found that a larger distance was beneficial in reducing the stress concentration. It was also found that trimming the corners of the continuity plate for the specimen whose column was much wider than the beam helps to reduce the stress concentration at the groove weld. Based on these analytical results and experimental tests, a design procedure for weak-axis RBS moment connections was developed.

Two of the three deep column specimens were able to reach 0.03 radian of plastic rotation without experiencing brittle fracture in the welded joints. The third specimen nearly reached 0.03 radian of plastic rotation before a brittle fracture developed along the k-line of the column. All of the deep column specimens experienced column twisting, which is a highly undesirable condition. The twisting of the deep columns is caused by two factors. First, introducing an RBS causes the beam to buckle more laterally. Second, the torsional properties of deep sections tend to produce higher warping stresses in the column. It was found that the h/t_f^3 ratio, where $h = d_c - t_f$, was mainly responsible for the higher warping stresses. A design verification procedure that would avoid twisting of the column was developed.

ACKNOWLEDGEMENTS

Funding for this research was provided by the Federal Emergency Management Agency through the SAC Joint Venture. SAC is a partnership of the Structural Engineers Association of California, the Applied Technology Council, and California Universities for Research in Earthquake Engineering. This research was conducted as part of Task 7.11 in Phase II of the SAC Joint Venture.

Mr. J.O. Malley was the Project Director of Topical Investigation. Mr. D. Long of PDM/Strocal donated the fabrication service. Dr. J.M. Barsom performed fracture analysis of one test specimen. Assistance during the test setup and testing of the specimens from the technical staff at the Powell Laboratories at the University of California, San Diego are greatly appreciated.

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