SAC
Steel Project

Background Document

Cyclic Response of RBS Moment Connections: Loading Sequence and Lateral Bracing Effects

Report No. SAC/BD-00/22

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 loading sequence and lateral bracing on the performance of welded web Reduced Beam Section (RBS) moment connections. Four full-scale specimens were tested two with a standard stepwise increasing loading history and two with a near-fault loading history. All four specimens behaved well, exceeding 0.03 radians of plastic rotation and avoided brittle fracture of the beam flange groove welds. The specimens tested with the near field loading history actually achieved somewhat higher rotation levels and demonstrated smaller buckling amplitudes. Energy dissipation of the different connections was very comparable. Additional lateral bracing was added to one connection to investigate the influence of performance. The lateral bracing did not increase the peak strength of the connection. Also, there was no appreciable increase in the energy dissipation until drift levels above 0.04 radians. The loads in the bracing elements were quite large, exceeding seven per cent of the beam flange strength at maximum displacements. Complementary finite element analyses were performed to better understand the influence of axial restraint effects that would occur in frame systems. It was found that frame restraint is very effective in reducing the lateral buckling and the strength degradation of the connections at larger deformations. It therefore appears that lateral bracing of RBS connections near the plastic hinges is not needed for good performance. This task was identified as part of Task 7.11 of the SAC Phase II program. The work 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 conducted to investigate the performance of steel moment frame connections that incorporate the reduced beam section (RBS) design. Four full-scale, welded web moment connections with reduced beam sections, were statically tested, two with a standard loading history and two with a near-fault loading history. All four specimens behaved well, reaching 0.03 radian of plastic rotation and avoiding brittle fracture of the beam flange groove welds. Interestingly, the specimens tested with the near-fault loading protocol were able to reach 0.05 radian of plastic rotation, nearly 70% more than the plastic rotation of the other specimens. It is expected that the plastic rotation capacity of the near-fault specimens would increase with added deformation demand. Furthermore, the specimens tested with the near-fault loading protocol experienced smaller buckling amplitudes at comparable drift levels than those experienced by the specimens tested with the standard loading protocol. Energy dissipation capacities of the specimens were insensitive to the type of loading protocol.

Additional lateral bracing was added near the RBS region of one of the specimens tested with the standard loading history. The incorporation of lateral bracing enabled the specimen to achieve 0.04 radian of plastic rotation, compared to the 0.03 radian of plastic rotation achieved by the specimen without bracing. The lateral bracing did not increase the beam maximum strength, but it was able to reduce the rate of strength degradation. Beyond 3% drift, the specimen with additional bracing recorded reduced buckling amplitudes and increased energy dissipation compared to the specimen without bracing. The peak axial force in the brace was determined to be about 7% of the compressive force in the beam flange.

A nonlinear finite element analysis concluded that the system axial restraining effects to the beams can significantly reduce the strength degradation at higher displacement levels by reducing the beam local buckling amplitudes. Adding lateral bracing near the RBS region of special moment resisting frame structures where axial restraining effects typically exist is unwarranted.

ACKNOWLEDGEMENT

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 must be acknowledged as the Project Director of Topical Investigations. The authors would like to thank PDM/Strocal, Asbury Steel, TSI Inc., AISC, and the Northridge Steel Industry Fund for their contributions to this project. 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. Gratitude must be extended to Mr. Brandon Chi for his assistance in preparation of the report.

TABLE OF CONTENTS

ABSTRACT i

ACKNOWLEDGEMENT ii

TABLE OF CONTENTS iii

LIST OF TABLES v

LIST OF FIGURES vi

LIST OF SYMBOLS ix

1. INTRODUCTION 1
    - 1.1 Statement of Problem 1
    - 1.2 Objectives and Scope 1

2. TESTING PROGRAM 2
    - 2.1 General 2
    - 2.2 Design Review 2
    - 2.3 Construction and Inspection 4
    - 2.4 Material Properties 5
    - 2.5 Test Set-up 6
    - 2.6 Loading Histories 6
    - 2.7 Instrumentation 6
    - 2.8 Data Reduction 7

3. TEST RESULTS 15
    - 3.1 General 15
    - 3.2 Specimen LS-1 15
    - 3.3 Specimen LS-2 17
    - 3.4 Specimen LS-3 19
    - 3.5 Specimen LS-4 21

4. PERFORMANCE COMPARISON AND DESIGN IMPLICATIONS 71
    - 4.1 General 71
    - 4.2 Loading History Effects 71
    - 4.3 Bracing Effects 72

5. CORRELATION STUDY 78
5.1 General 78
5.2 Modeling Techniques and Assumptions 78
5.3 Correlation of Analytical Predictions with Experimental Results 79
6. ANALYTICAL STUDY OF SYSTEM RESTRAINING EFFECTS 84
6.1 General 84
6.2 Modeling Techniques 84
6.3 Behavior Comparison 85
6.4 Implications of System Restraining Effects 86
7. SUMMARY AND CONCLUSIONS 91
7.1 Summary 91
7.2 Conclusions 91
REFERENCES 93
APPENDIX A: WELD PROCEDURE SPECIFICATIONS 95
APPENDIX B: WELDING INSPECTION REPORT 108