SAC
Steel Project

Background Document

Seismic Performance of 3 and 9 Story Partially Restrained Moment Frame Buildings

Report No. SAC/BD-99/16

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
Bruce F. Maison
Structural Engineer
Kazuhiko Kasai
Tokyo Institute of Technology

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

June 2000

DISCLAIMER

SAC
Steel Project

Background Document

Seismic Performance of 3 and 9 Story Partially Restrained Moment Frame Buildings

Report No. SAC/BD-99/16

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
Bruce F. Maison
Structural Engineer
Kazuhiko Kasai
Tokyo Institute of Technology

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

June 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 reports documents an analytical investigation into seismic performance of two buildings designed with partially restrained (PR) connections as the main elements in the lateral force resisting system. A three story and nine story building were designed for this analysis. The buildings were redesigns of buildings previously designed using fully restrained (FR) connections. Member sizes and connection stiffnesses and capacities were all re-designed for the PR designs. Nonlinear time history analyses were performed on a suite of ground motions to compare the performance with the FR designs. The analyses generally indicated that the performance was similar to that of the FR frame. The local connection demands appeared to be generally within the limits of the capacities demonstrated in physical testing. This study indicates that buildings designed with PR connections may acceptable performance in regions subjected to high seismic demands. This report comprises part of the work completed as part of Task 5.4.7 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 System Performance, selected members of the Connection Performance TAP; and several members of the Project Oversight Committee. The contributions of these individuals are greatly appreciated.

SEISMIC PERFORMANCE OF 3 AND 9 STORY PARTIALLY RESTRAINED MOMENT FRAME BUILDINGS

Bruce F. Maison
STRUCTURAL ENGINEER

Kazuhiko Kasai
TOKYO INSTITUTE OF TECHNOLOGY

SAC Joint Venture Report Number:
SAC/BD-99/16
June 2000

SUMMARY

This report contains a study into the seismic performance of two buildings having partially restrained (PR) moment frame lateral load resisting structural systems:

3-Story Building designed for Los Angeles, California,
9-Story Building designed for Seattle, Washington.

The buildings are redesigns of SAC model buildings. The building footprints, column spacing, story heights and live loads are the same as those for the SAC welded steel moment frame (WSMF) model buildings having fully restrained (FR) connections. The columns, girders and connections were proportioned using state-of-practice techniques for PR frame buildings by a consulting firm experienced with such design. The seismic performance is studied by via numerous computer nonlinear analyses of building models using suites of earthquake ground motions previously developed by SAC.

Key observations from this study are as follows.

1. The PR building seismic performance is similar to that of the ductile performance (i.e., "pre-Northidge intended") of the corresponding FR WSMF building. For the Los Angeles buildings, the PR drifts are generally greater than those from the FR, and vice versa for the Seattle buildings. Pre-Northridge intended performance reflects no fracture of WSMF connections, and therefore the actual FR drifts would likely be larger with fractured connections. The PR buildings were purposely designed for base shears similar in magnitude as the corresponding FR buildings. Strict adherence to building code provisions would have larger PR design base shears which would result with stronger PR buildings having better performance.

2. The PR connection rotation demands are significant, but the median demands are probably attainable with well designed connection details, i.e., ensuring ductile components control behavior.
3. Peak story drift is a good predictor of peak PR connection rotation demand. A regression of peak rotation and peak story drift indicates that the peak connection rotation at a particular story is typically only slightly greater than the corresponding peak story drift.

The writers conclude that PR buildings have the potential for successful use in seismic regions, but there are issues that must be addressed prior to their acceptance. These include:

1. More PR connection tests are needed on deep beam configurations with realistic earthquake loading patterns to establish a repertoire of reliable connection types and appropriate capacity limits for design. The PR building designs were based current industry PR connection experience. Stiffer and stronger PR connections would enhance the performance of both case study buildings. The SAC connection test program includes T-stub, clip angle, end plate and bolted flange plate types, and the results from these tests will help address this issue.
2. The economics of PR construction must compare favorably to competing structural systems. The SAC guidelines will have a variety of connection configurations including PR types. For example, reduced beam section (RBS) moment frame systems will emerge from SAC as one possible replacement for the pre-Northridge WSMF type system. Such buildings can have relatively few expensive RBS connections located in perimeter frames and many relatively cheap shear tab connections on the interior gravity frames (much like many pre-Northridge FR WSMF buildings). Competing PR buildings will have all connections of intermediate cost PR types. The relative costs of the two framing systems are not yet clear, but the lowest cost system will be favored. The most economical systems will become apparent only after designers apply the SAC guidelines in practice.
3. Building codes must allow PR construction to compete with other systems on an equitable basis. The current study uses the same lateral force and drift design criteria as that for FR construction, and the seismic performance of both LFRS is found to be similar. If codes penalize PR construction with unfavorable provisions having no real foundation, then PR construction will not be cost effective. The 1994 UBC assigns the PR building response modification R_w factor one-half that for FR buildings (meaning that PR building lateral design forces are twice those for FR buildings). The 1997 NEHRP provisions closes the gap by having smaller differences in response modification R factors between special moment frames and certain types of PR moment frame construction (FEMA 302, 1998). In addition, the benefits of high redundancy inherent to PR buildings is favorably reflected in the NEHRP reliability coefficient.

CONTENTS

1 Introduction

2 Los Angeles 3-Story PR Building

3 Los Angeles Earthquake Ground Motions

4 Los Angeles Building Analysis Model
- 4.1 Number of Frames
- 4.2 Girder Modeling
- 4.3 Column Modeling
- 4.4 PR Connection Modeling
- 4.5 Gravity Loading
- 4.6 P-delta Effects
- 4.7 Mass
- 4.8 Damping
- 4.9 Dynamic Properties
- 4.10 Pushover Lateral Force Pattern

5 Los Angeles Building Electronic Data Files
- 5.1 Pushover Analysis Results
- 5.2 Time History Results: 10% / 50 Years
- 5.3 Time History Results: 2% / 50 Years
- 5.4 Time History Results: 50% / 50 Years

6 PR Connection Rotation Demands

7 Los Angeles PR and FR Building Comparison
- 7.1 Building Properties
- 7.2 Pushover Results
- 7.3 Time History Results

8 Seattle 9-Story PR Building

9 Seattle Earthquake Ground Motions

10 Seattle Building Analysis Model
- 10.1 Number of Frames
- 10.2 Girder Modeling
- 10.3 Column Modeling
- 10.4 PR Connection Modeling

10.5 Gravity Loading
10.6 P-delta Effects
10.7 Mass
10.8 Damping
10.9 Dynamic Properties
10.10 Pushover Lateral Force Pattern

11 Seattle Building Electronic Data Files
11.1 Pushover Analysis Results
11.2 Time History Results: 10% / 50 Years
11.3 Time History Results: 2% / 50 Years

12 PR Connection Rotation Demands

13 Seattle PR and FR Building Comparison
13.1 Building Properties
13.2 Pushover Results
13.3 Time History Results

14 Conclusions

15 References
16 Acknowledgments

Appendix A: Design Methodology For 3- and 9- Story PR Buildings

A1 General
A2 SDLAL Design Experience with PR Buildings
A3 Design Criteria
A3.1 Loads
A3.1.1 Typical Gravity Loads
A3.1.2 Seismic Loads
A3.2 Strength Criteria
A3.3 Drift Criteria
A4 Design Philosophy
A5 Design Process
A6 Analysis Assumptions
A6.1 General
A6.2 Connection Selection, Behavior and Detailing
A7 Analysis Procedure
A8 Discussion of Nine Story Building Design
A9 References