BACKGROUND REPORTS: Metallurgy, Fracture Mechanics, Welding, Moment Connections and Frame Systems Behavior

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SAC Joint Venture

a partnership of:
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Applied Technology Council (ATC)
California Universities for Research in Earthquake Engineering (CUREe)

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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 the problems of the Welded Steel Moment Frame (WSMF) connection. 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* as well as the *National Earthquake Hazards Reduction Program (NEHRP) Recommended Provisions for Seismic Regulations for New Buildings.* The Applied Technology Council is a non-profit organization founded specifically to perform problem-focused research related to structural engineering and to bridge the gap between civil engineering research and engineering practice. It has developed a number of publications of national significance including ATC 3-06, which serves as the basis for the *NEHRP Recommended Provisions.* CUREe is a non-profit 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. This collection of university earthquake research laboratory, library, computer and faculty resources is 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 around the nation, into an integrated team of practitioners and researchers, uniquely qualified to solve problems related to the seismic performance of WSMF structures.

DISCLAIMER

This report is one of a series documenting a preliminary program of laboratory, field and analytical investigations and research conducted as part of Phase 1 of the Program to Reduce Earthquake Hazards of Steel Moment Frame Structures conducted by the SAC Joint Venture under funding from the Federal Emergency Management Agency. Information contained in this report was used in the development of the *Interim Guidelines: Evaluation, Repair, Modification and Design of Welded Steel Moment Frame Structures* (FEMA Report No. 267, August 1995). This report is being published to improve understanding of the basis for the *Interim Guidelines* and of the factors contributing to the seismic performance of steel moment frame structures. Opinions and recommendations contained in this report are those of the respective contributing author(s) and do not necessarily represent an official position of the SAC Joint Venture

The work contained in this report has been reviewed by a Technical Advisory Panel, comprising experts from a variety of fields, and the Project Technical Committee. Every attempt has been made to ensure its accuracy. However, it must be recognized that the report is of limited scope and has been completed within a short period of time. As a consequence, it may not account for work undertaken in other parts of the SAC Phase 1 Steel Project or by others; it may not address all of the facets of a problem in a consistent fashion; and it may contain information contrary to that incorporated into the *Interim Guidelines* or obtained in other SAC-directed investigations or in other investigations. The reader is cautioned that research is continuing at a rapid pace in this field, and that results of this continuing research may invalidate or suggest the need for modification of the results or recommendations contained herein.

No warranty is offered with regard to the results, findings and recommendations contained herein, either by the Federal Emergency Management Agency, the SAC Joint Venture, the individual joint venture partners, their directors, members or employees. These organizations and individuals do not assume any legal liability or responsibility for the accuracy, completeness, or usefulness of any of the information, products or processes included in this publication. The reader is cautioned to carefully review the material presented herein.

PREFACE

The Northridge Earthquake of January 17, 1994, dramatically demonstrated that the prequalified, welded beam-to-column moment connection commonly used in the construction of welded steel moment resisting frames (WSMFs) in the period 1970-1994 was much more susceptible to damage than previously thought. The stability of moment frame structures in earthquakes is dependent on the capacity of the beam-column connection to remain intact and to resist tendencies of the beams and columns to rotate with respect to each other under the influence of lateral swaying of the structure. The prequalified connections were believed to be ductile and capable of withstanding the repeated cycles of large inelastic deformation explicitly relied upon in the building code provisions for the design of these structures. Although many affected connections were not damaged, a wide spectrum of unexpected brittle connection fractures did occur, ranging from minor cracking observable only by detailed nondestructive testing (NDT) to complete severing of columns. At the time this damage was discovered, the structural steel industry and engineering profession had little understanding of the specific causes of this damage, the implications of this damage for building safety, or even if reliable methods existed to repair the damage which had been discovered. While no casualties or collapses occurred as a result of these connection failures, and some welded steel moment frame (WSMF) buildings were not damaged, the incidence of damage was sufficiently high in regions of strong ground motion to cause wide-spread concern by structural engineers and building officials with regard to the safety of these structures in seismically active regions.

In response to these concerns, the Federal Emergency Management Agency (FEMA) entered into a cooperative agreement with the SAC Joint Venture to perform a problem focused study of the seismic performance of welded steel moment connections and to develop interim recommendations for professional practice. Specifically, these recommendations were intended to address the inspection of earthquake affected buildings to determine if they had sustained significant damage; the repair of damaged buildings; the upgrade of existing buildings to improve their probable future performance; and the design of new structures to provide more reliable seismic performance. Within weeks of receipt of notification of FEMA's intent to enter into this agreement, the SAC Joint Venture published a series of two Design Advisories (SAC, 1994a; SAC, 1994b) These Design Advisories presented a series of papers, prepared by engineers and researchers engaged in the investigation of the damaged structures and presenting individual opinions as to the causes of the damage, potential methods of repair, and more reliable design of connections in the future. In February, 1995, Design Advisory No. 3 (SAC, 1995a) was published. This third advisory presented a synthesis of the data presented in the earlier publications, together with the preliminary recommendations developed in an industry workshop, attended by more than 50 practitioners, industry representatives and researchers, on methods of inspecting, repairing and designing WSMF structures. At the time this third advisory was published, significant disagreement remained within the industry and the profession as to the specific causes of the damage observed and appropriate methods for practice given that the damage had occurred. Consequently, the preliminary recommendations were presented as a series of issue statements, followed by the consensus opinions of the workshop attendees, where

consensus existed, and by majority and dissenting opinions where such consensus could not be formed.

During the first half of 1995, an intensive program of research was conducted to more definitively explore the pertinent issues. This research included literature surveys, data collection on affected structures, statistical evaluation of the collected data, analytical studies of damaged and undamaged buildings and laboratory testing of a series of full-scale beam-column assemblies representing typical pre-Northridge design and construction practice as well as various repair, upgrade and alternative design details. The findings of this research (SAC, 1995c; SAC, 1995d; SAC, 1995e; SAC, 1995f; SAC, 1995g; SAC, 1995h; SAC, in preparation) were used in the development of FEMA 267 *Interim Guidelines: Evaluation, Repair, Modification, and Design of Welded Steel Moment Frame Structures* (SAC, 1995b) in August, 1995. FEMA 267 provided the first definitive, albeit interim, recommendations for practice, following the discovery of connection damage in the Northridge earthquake.

As a result of these studies as well as independent research conducted by others, it is now known that a large number of factors contributed to the damage sustained by steel frame buildings in the Northridge earthquake. These included:

- design practice that favored the use of relatively few frame bays to resist lateral seismic demands, resulting in much larger member and connection geometries than had previously been tested
- standard detailing practice that resulted in the development of large inelastic demands at the beam to column connections
- detailing practice that often resulted in large stress concentrations in the beam-column connection
- the common use of welding procedures that resulted in deposition of low toughness weld metal in the critical beam flange to column flange joints
- relatively low levels of quality control and assurance in the construction process, resulting in welded joints that did not conform to the applicable quality standards
- detailing practice for welded joints that resulted in inherent stress risers and notches in zones of high stress
- excessively weak and flexible column panel zones that resulted in large secondary stresses in the beam flange to column flange joints
- large variations in material strengths relative to specified values
- the inherent inability of the material to yield under conditions of high tri-axial restraint such as exist at the center of the beam flange to column flange joints

In addition to these technical issues, review of the state-of-practice at the time of the Northridge earthquake indicated that many engineers engaged in the design of steel frames did not possess adequate knowledge or understanding of the basic materials and processes they were relying upon and specifying in their designs. The presence of a highly prescriptive set of building code provisions and industry standards resulted in a situation of near blind reliance on the efficacy of these standards and limited effort on the part of engineers to understand their basis, limits of applicability and critical issues pertinent to their application.

On the basis of preliminary research performed following the Northridge Earthquake, FEMA-267 was published in August, 1995. FEMA-267 presents an interim recommended design methodology to provide connections capable of more reliable seismic performance, as well as recommendations for the inspection, evaluation, repair and upgrade of existing buildings. Unlike previous engineering standards for these structures, the FEMA-267 recommendations require the engineer to exercise a high degree of judgment and understanding of the critical issues pertinent to steel moment-frame performance. The background papers contained in this publication are intended to provide a portion of the primary background information required to exercise such understanding and judgment. They provide a summary of the state of knowledge with regard to the production and properties of structural use steels, welding processes and procedures, fracture mechanics, the behavior of various types of welded and bolted connections and methods of predicting the demands on these connections using frame analysis, as it existed at the time of publication.

SAC is continuing, with FEMA funding, to perform additional research into the performance of moment resisting connections of various configurations. This work includes analytical evaluations of buildings and connections as well as additional large scale testing of connection assemblies. It is expected that in the course of these additional investigations, new information will be found that will either supplement or alter the validity of material presented in this publication. The SAC Joint Venture intends to prepare and FEMA to publish supplemental materials as appropriate.

It should be noted that individual authors of some papers have presented personal opinions and interpretations of the data presented, in some cases coupled with design recommendations. Engineers are cautioned to review the material presented carefully and to form their own opinions as to appropriate courses of action in applying this information. The opinions and recommendations contained herein do not necessarily reflect the recommendations of the Federal Emergency Management Agency, the SAC Joint Venture, or their individual employees, officers and directors.

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For additional information about the SAC Program to Reduce the Earthquake Hazards of Steel Moment Frame Structures see Appendix A.

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TABLE OF CONTENTS