

**Program to Reduce the Earthquake Hazards of
Steel Moment-Frame Structures**

Recommended Seismic Design Criteria for New Steel Moment-Frame Buildings

DISCLAIMER

This document provides recommended criteria for the design of steel moment-frame buildings to resist the effects of earthquakes. These recommendations were developed by practicing engineers, based on professional judgment and experience, and by a program of laboratory, field and analytical research. While every effort has been made to solicit comments from a broad selection of the affected parties, this is not a consensus document. It is primarily intended as a resource document for organizations with appropriate consensus processes for the development of future design standards and building code provisions. **No warranty is offered, with regard to the recommendations contained herein, either by the Federal Emergency Management Agency, the SAC Joint Venture, the individual Joint Venture partners, or their directors, members or employees. These organizations and their employees 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 review carefully the material presented herein and exercise independent judgment as to its suitability for application to specific engineering projects.** These recommended criteria have been prepared by the SAC Joint Venture with funding provided by the Federal Emergency Management Agency, under contract number EMW-95-C-4770.

Cover Art. The beam-column connection assembly shown on the cover depicts the standard detailing used in welded steel moment-frame construction prior to the 1994 Northridge earthquake. This connection detail was routinely specified by designers in the period 1970-1994 and was prescribed by the *Uniform Building Code* for seismic applications during the period 1985-1994. It is no longer considered to be an acceptable design for seismic applications. Following the Northridge earthquake, it was discovered that many of these beam-column connections had experienced brittle fractures at the joints between the beam flanges and column flanges.

Recommended Seismic Design Criteria for New Steel Moment-Frame Buildings

SAC Joint Venture

**A partnership of
Structural Engineers Association of California (SEAOC)
Applied Technology Council (ATC)
California Universities for Research in Earthquake Engineering (CUREe)**

**Prepared for SAC Joint Venture Partnership by
Guidelines Development Committee**

Ronald O. Hamburger, Chair

John D. Hooper
Robert Shaw
Lawrence D. Reaveley

Thomas Sabol
C. Mark Saunders
Raymond H. R. Tide

Project Oversight Committee

William J. Hall, Chair

Shirin Ader
John M. Barsom
Roger Ferch
Theodore V. Galambos
John Gross
James R. Harris
Richard Holguin

Nestor Iwankiw
Roy G. Johnston
Leonard Joseph
Duane K. Miller
John Theiss
John H. Wiggins

SAC Project Management Committee

SEAOC: William T. Holmes
ATC: Christopher Rojahn
CUREe: Robin Shepherd

Program Manager: Stephen A. Mahin
Project Director for Topical Investigations:
James O. Malley
Project Director for Product Development:
Ronald O. Hamburger

SAC Joint Venture

SEAOC: www.seaoc.org
ATC: www.atcouncil.org
CUREe: www.curee.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 university earthquake research 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 consultants and 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 structures.

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.

TABLE OF CONTENTS

LIST OF FIGURES	ix
LIST OF TABLES.....	xi
1 INTRODUCTION.....	1-1
1.1 Purpose.....	1-1
1.2 Intent	1-2
1.3 Background	1-3
1.4 Application.....	1-10
1.5 Overview	1-10
2 GENERAL REQUIREMENTS	2-1
2.1 Scope.....	2-1
2.2 Applicable Codes, Standards, and References.....	2-1
2.3 Basic Design Approach.....	2-2
2.4 Design Performance Objectives.....	2-3
2.5 System Selection	2-7
2.5.1 Configuration and Load Path	2-7
2.5.2 Structural System Selection	2-7
2.5.3 Connection Type	2-8
2.5.4 Redundancy.....	2-9
2.5.5 Frame Beam Spans.....	2-10
2.6 Structural Materials.....	2-11
2.6.1 Material Specifications	2-11
2.6.2 Material Strength Properties	2-12
2.7 Structural Analysis.....	2-13
2.8 Mathematical Modeling	2-13
2.8.1 Basic Assumptions.....	2-13
2.8.2 Model Configuration.....	2-14
2.8.2.1 Regularity.....	2-14
2.8.2.2 Elements Modeled	2-14
2.1.1.3 Connection Stiffness	2-15
2.1.3 Horizontal Torsion	2-16
2.1.4 Foundation Modeling.....	2-16
2.1.5 Diaphragms	2-17
2.1.6 <i>P-D</i> Effects	2-17
2.1.7 Multidirectional Excitation Effects.....	2-20
2.1.8 Vertical Excitation	2-20
2.9 Frame Design	2-21
2.9.1 Strength of Beams and Columns.....	2-21
2.1.2 Lateral Bracing of Column Flanges	2-22
2.1.3 Panel Zone Strength.....	2-22
2.1.4 Section Compactness Requirements	2-23
2.1.5 Beam Lateral Bracing	2-23

2.1.6	Deep Columns.....	2-23
2.1.7	Built-up Sections.....	2-24
2.2	Connection Design.....	2-24
2.3	Specifications.....	2-25
2.4	Quality Control and Quality Assurance	2-26
2.5	Other Structural Connections.....	2-26
2.5.1	Column Splices.....	2-26
2.5.2	Column Bases	2-28
2.5.3	Welded Collectors and Chords	2-29
2.5.4	Simple Beam-to-Column Gravity Connections	2-29
3	CONNECTION QUALIFICATION	3-1
3.1	Scope.....	3-1
3.2	Basic Design Approach.....	3-2
3.2.1	Frame Configuration	3-2
3.2.2	Connection Configuration.....	3-5
3.2.3	Determine Plastic Hinge Locations.....	3-5
3.2.4	Determine Probable Plastic Moment at Hinges	3-6
3.2.5	Determine Shear at the Plastic Hinge	3-7
3.2.6	Determine Strength Demands at Each Critical Section	3-7
3.2.7	Yield Moment	3-8
3.3	General Requirements.....	3-9
3.3.1	Beams.....	3-9
3.3.1.1	Beam Flange Stability	3-9
3.3.1.2	Beam Web Stability	3-10
3.3.1.3	Beam Depth and Span Effects	3-10
3.3.1.4	Beam Flange Thickness Effects	3-11
3.3.1.5	Lateral Bracing at Beam Flanges at Plastic Hinges	3-11
3.3.1.6	Welded Shear Studs	3-12
3.3.2	Welded Joints.....	3-12
3.3.2.1	Through-Thickness Strength.....	3-12
3.3.2.2	Base Material Toughness	3-13
3.3.2.3	k-Area Properties	3-14
3.3.2.4	Weld Metal Matching and Overmatching.....	3-15
3.3.2.5	Weld Metal Toughness	3-15
3.3.2.6	Weld Backing, Weld Tabs and Other Details	3-16
3.3.2.7	Weld Access Holes	3-17
3.3.2.8	Welding Quality Control and Quality Assurance	3-17
3.3.3	Other Design Issues for Welded Connections	3-19
3.3.3.1	Continuity Plates.....	3-19
3.3.3.2	Panel Zone Strength.....	3-21
3.3.3.3	Connections to Column Minor Axis.....	3-22
3.3.3.4	Attachment of Other Construction.....	3-22
3.3.4	Bolted Joints	3-23
3.4	Prequalified Connections – General	3-23

3.4.1	Load Combinations and Resistance Factors	3-25
3.5	Prequalified Welded Fully Restrained Connections	3-25
3.5.1	Welded Unreinforced Flange – Bolted Web Connections.....	3-26
3.5.1.1	Design Procedure	3-28
3.5.2	Welded Unreinforced Flange – Welded Web Connections	3-28
3.5.2.1	Design Procedure	3-31
3.5.3	Free Flange Connections.....	3-31
3.5.3.1	Design Procedure	3-33
3.5.4	Welded Flange Plate Connections	3-34
3.5.4.1	Design Procedure	3-37
3.5.5	Reduced Beam Section Connections	3-38
3.5.5.1	Design Procedure	3-41
3.5.5.2	Fabrication Requirements	3-42
3.5.5.3	Composite Construction	3-42
3.6	Prequalified Bolted Fully Restrained Connections	3-42
3.6.1	Bolted Unstiffened End Plate Connections.....	3-42
3.6.1.1	Design Procedure	3-45
3.6.2	Bolted Stiffened End Plate Connection	3-48
3.6.2.1	Design Procedure	3-51
3.6.3	Bolted Flange Plate Connections	3-53
3.6.3.1	Design Procedure	3-56
3.7	Prequalified Partially Restrained Connections	3-59
3.7.1	Double Split Tee Connections	3-60
3.7.1.1	Connection Stiffness	3-63
3.7.1.2	Design Procedure	3-63
3.8	Proprietary Connections.....	3-68
3.8.1	Side Plate	3-68
3.8.2	Slotted Web.....	3-70
3.8.3	Bolted Bracket.....	3-72
3.8.4	Reduced Web	3-72
3.9	Project-Specific Connection Qualification	3-73
3.9.1	Testing Procedures.....	3-74
3.9.2	Acceptance Criteria.....	3-76
3.9.3	Analytical Prediction of Behavior.....	3-78
3.10	Prequalification Testing Criteria.....	3-78
3.10.1	Prequalification Testing.....	3-79
3.10.2	Extending the Limits on Prequalified Connections	3-79
4	PERFORMANCE EVALUATION	4-1
4.1	Scope.....	4-1
4.2	Performance Definition.....	4-1
4.2.1	Hazard Specification.....	4-3
4.2.1.1	General	4-3
4.2.1.2	Ground Shaking.....	4-3
4.2.1.3	Other Hazards.....	4-5

4.2.2	Performance Levels.....	4-5
4.2.2.1	Nonstructural Performance Levels	4-7
4.2.2.2	Structural Performance Levels	4-7
4.2.2.2.1	Collapse Prevention Performance Level	4-8
4.2.2.2.2	Immediate Occupancy Performance Level	4-8
4.3	Evaluation Approach	4-10
4.4	Analysis.....	4-11
4.4.1	Alternative Procedures.....	4-11
4.4.2	Procedure Selection	4-13
4.4.3	Linear Static Procedure	4-13
4.4.3.1	Basis of the Procedure.....	4-13
4.4.3.2	Period Determination	4-15
4.4.3.3	Determination of Actions and Deformations	4-16
4.4.3.3.1	Pseudo Lateral Load.....	4-16
4.4.3.3.2	Vertical Distribution of Seismic Forces.....	4-18
4.4.3.3.3	Horizontal Distribution of Seismic Forces	4-18
4.4.3.3.4	Diaphragms	4-18
4.4.3.3.5	Determination of Interstory Drift	4-18
4.4.3.3.6	Determination of Column Demands	4-19
4.4.4	Linear Dynamic Procedure.....	4-19
4.4.4.1	Basis of the Procedure.....	4-19
4.4.4.2	Analysis.....	4-20
4.4.4.2.1	General	4-20
4.4.4.2.2	Ground Motion Characterization	4-21
4.4.4.3	Determination of Actions and Deformations	4-21
4.4.4.3.1	Factored Interstory Drift Demand	4-21
4.4.4.3.2	Determination of Column Demands	4-21
4.4.5	Nonlinear Static Procedure	4-21
4.4.5.1	Basis of the Procedure.....	4-21
4.4.5.2	Analysis Considerations.....	4-22
4.4.5.2.1	General	4-22
4.4.5.2.2	Control Node.....	4-23
4.4.5.2.3	Lateral Load Patterns	4-24
4.4.5.2.4	Period Determination	4-24
4.4.5.2.5	Analysis of Three-Dimensional Models	4-24
4.4.5.2.6	Analysis of Two-Dimensional Models	4-24
4.4.5.3	Determination of Actions and Deformations	4-24
4.4.5.3.1	Target Displacement	4-24
4.4.5.3.2	Diaphragms	4-24
4.4.5.3.3	Factored Interstory Drift Demand	4-24
4.4.5.3.4	Multidirectional effects.....	4-25
4.4.5.3.5	Factored Column and Column Splice Demands...	4-25
4.4.6	Nonlinear Dynamic Procedure.....	4-25
4.4.6.1	Basis of the Procedure.....	4-25

4.4.6.2	Analysis Assumptions.....	4-25
4.4.6.2.1	General	4-25
4.4.6.2.2	Ground Motion Characterization	4-26
4.4.6.3	Determination of Actions and Deformations	4-26
4.4.6.3.1	Response Quantities.....	4-26
4.4.6.3.2	Factored Interstory Drift Demand	4-26
4.4.6.3.3	Factored Column and Column Splice Demands...	4-26
4.5	Mathematical Modeling	4-26
4.5.1	Basic Assumptions	4-26
4.5.2	Frame Configuration.....	4-27
4.5.2.1	Modeling.....	4-27
4.5.2.2	Connection Modeling.....	4-28
4.5.2.2.1	Fully Restrained Moment-Resisting Connections.....	4-28
4.5.2.2.2	Partially Restrained Moment-Resisting Connections.....	4-28
4.5.2.2.3	Simple Shear Tab Connections.....	4-29
4.5.2.3	Panel Zone Stiffness	4-29
4.5.3	Horizontal Torsion	4-30
4.5.4	Foundation Modeling.....	4-31
4.5.5	Diaphragms	4-31
4.5.6	<i>P-D</i> Effects	4-32
4.5.7	Multidirectional Excitation Effects.....	4-32
4.5.8	Vertical Ground Motion.....	4-32
4.6	Acceptance Criteria	4-33
4.6.1	Factored-Demand-to Capacity Ratio.....	4-33
4.6.2	Performance Limited By Interstory Drift Angle	4-36
4.6.2.1	Factored Interstory Drift Angle Demand	4-36
4.6.2.2	Factored Interstory Drift Angle Capacity.....	4-37
4.6.2.2.1	Global Interstory Drift Angle.....	4-37
4.6.2.2.2	Local Interstory Drift Angle.....	4-37
4.6.3	Performance Limited by Column Compressive Capacity.....	4-40
4.6.3.1	Column Compressive Demand	4-40
4.6.3.2	Column Compressive Capacity.....	4-42
4.6.4	Column Splice Capacity.....	4-42
4.6.4.1	Column Splice Tensile Demand	4-42
4.6.4.2	Column Splice Tensile Capacity.....	4-42
APPENDIX A: DETAILED PROCEDURE FOR PERFORMANCE EVALUATION		A-1
A.1	Scope.....	A-1
A.2	Performance Evaluation Approach	A-1
A.2.1	Performance Objectives and Confidence	A-1
A.2.2	Basic Procedure.....	A-4
A.3	Determination of Hazard Parameters.....	A-7
A.3.1	Spectral Response Acceleration.....	A-7

A.3.2	Logarithmic Hazard Curve Slope	A-7
A.4	Determination of Demand Factors	A-10
A.5	Determination of Beam-Column Connection Assembly Capacities	A-13
A.5.1	Connection Test Protocols	A-14
A.5.2	Determination of Beam-Column Assembly Capacities and Resistance Factors	A-14
A.6	Global Stability Capacity	A-15
REFERENCES, BIBLIOGRAPHY, AND ACRONYMS		R-1
SAC PROJECT PARTICIPANTS		S-1

LIST OF FIGURES

Figure 1-1	Typical Welded Moment-Resisting Connection Prior to 1994.....	1-4
Figure 1-2	Common Zone of Fracture Initiation in Beam-Column Connection	1-5
Figure 1-3	Fractures of Beam-to-Column Joints	1-5
Figure 1-4	Column Fractures.....	1-6
Figure 1-5	Vertical Fracture through Beam Shear Plate Connection	1-6
Figure 2-1	NEHRP Seismic Use Groups (SUG) and Performance	2-4
Figure 2-2	Interstory Drift Angle.....	2-9
Figure 3-1	Inelastic Behavior of Frames with Hinges in Beam Span.....	3-3
Figure 3-2	Location of Plastic Hinge Formation	3-6
Figure 3-3	Sample Calculation of Shear at Plastic Hinge	3-8
Figure 3-4	Calculation of Demands at Critical Sections	3-8
Figure 3-5	Recommended Weld Access Hole Detail	3-18
Figure 3-6	Typical Continuity and Doubler Plates	3-20
Figure 3-7	Welded Unreinforced Flange – Bolted Web (WUF-B) Connection.....	3-26
Figure 3-8	Welded Unreinforced Flange – Welded Web (WUF-W) Connection.....	3-29
Figure 3-9	Welded Free Flange (FF) Connection.....	3-33
Figure 3-10	Schematic of the Forces for Design of the Free Flange Shear Tab	3-35
Figure 3-11	Welded Flange Plate (WFP) Connection.....	3-36
Figure 3-12	Reduced Beam Section (RBS) Connection.....	3-39
Figure 3-13	Bolted Unstiffened End Plate (BUEP) Connection	3-43
Figure 3-14	Geometry of Unstiffened End Plate Connection.....	3-48
Figure 3-15	Stiffened End Plate Connection	3-49
Figure 3-16	Geometry of Stiffened End Plate Connection.....	3-53
Figure 3-17	Bolted Flange Plate (BFP) Connection.....	3-54
Figure 3-18	Geometry of the Bolted Flange Plate Connection.....	3-56
Figure 3-19	Block Shear and Pull-Through Failures.....	3-59
Figure 3-20	Double Split Tee (DST) Connection.....	3-61
Figure 3-21	Geometry for Prying Forces and Bending of T-Section Flanges	3-64
Figure 3-22	Geometry for Other T-Stub Failure Modes.....	3-64
Figure 3-23	Proprietary Side Plate Connection	3-69
Figure 3-24	Proprietary Slotted Web Connection	3-71
Figure 3-25	Bolted Bracket Connection	3-72
Figure 3-26	Reduced Web Connection.....	3-73
Figure 3-27	Angular Rotation of Test Assembly.....	3-74
Figure A-1	Representative Incremental Dynamic Analysis Plots	A-17

LIST OF TABLES

Table 2-1	Values of R_y for Various Material Grades	2-12
Table 2-2	Prequalified Connection Details	2-25
Table 3-1	Prequalified Welded Fully Restrained Connections	3-25
Table 3-2	Prequalification Data WUF-B Connections.....	3-27
Table 3-3	Prequalification Data WUF-W Connections	3-30
Table 3-4	Prequalification Data for Free Flange Connections	3-32
Table 3-5	Prequalification Data for WFP Connections.....	3-35
Table 3-6	Prequalification Data for RBS Connections	3-40
Table 3-7	Prequalified Bolted Fully Restrained Connections	3-42
Table 3-8	Prequalification Data for BUEP Connections.....	3-44
Table 3-9	Prequalification Data for Bolted Stiffened End Plate Connections	3-50
Table 3-10	Prequalification Data for Bolted Flange Plate Connections	3-55
Table 3-11	Prequalified Bolted Partially Restrained Connections.....	3-60
Table 3-12	Prequalification Data for Full Strength DST Connections (FSDST).....	3-62
Table 3-13	Interstory Drift Angle Limits for Various Performance Levels	3-74
Table 3-14	Numerical Values of q_j and n_j	3-75
Table 3-15	Minimum Qualifying Total Interstory Drift Angle Capacities, q_{SD} , and q_U for OMF and SMF Systems	3-76
Table 4-1	Building Performance Levels.....	4-6
Table 4-2	Structural Performance Levels.....	4-8
Table 4-3	Analysis Procedure Selection Criteria	4-14
Table 4-4	Modification Factor C_3 for the Linear Static Procedure	4-18
Table 4-5	Performance Parameters Requiring Evaluation of Confidence	4-33
Table 4-6	Confidence Levels for Various Values of l , Given b_{UT}	4-35
Table 4-7	Recommended Minimum Confidence Levels.....	4-35
Table 4-8	Interstory Drift Angle Analysis Uncertainty Factors g_a	4-36
Table 4-9	Interstory Drift Angle Demand Variability Factors g	4-37
Table 4-10	Global Interstory Drift Angle Capacity C and Resistance Factors f for Regular SMF and OMF Buildings	4-38
Table 4-11	Uncertainty Coefficient b_{UT} for Global Interstory Drift Evaluation	4-38
Table 4-12	Drift Angle Capacity $C(q_{10}, q_U)$ for Prequalified Connections as Limited by Local Connection Response	4-39
Table 4-13	Uncertainty Coefficient b_{UT} for Local Interstory Drift Evaluation	4-40
Table 4-14	Behavior States for Performance Evaluation of Connection Assemblies.....	4-40
Table 4-15	Analysis Uncertainty Factor g_a and Total Uncertainty Coefficient b_{UT} for Evaluation of Column Compressive Demands	4-41
Table A-1	Confidence Parameter, l , as a Function of Confidence Level, Hazard Parameter k , and Uncertainty b_{UT}	A-8
Table A-2	Default Values of the Logarithmic Hazard Curve Slope k for Probabilistic Ground Shaking Hazards	A-9

Table A-3	Default Logarithmic Uncertainty b_{DU} for Various Analysis Methods	A-12
Table A-4	Default Bias Factors C_B	A-12
Table A-5	Behavior States for Performance Evaluation of Connection Assemblies	A-14