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DESIGN AND CONSTRUCTION STANDARDS FOR STEEL CONNECTIONS IN SEISMIC FRAMES

R.E. Shaw[1] and J.O. Malley[2]

[1] *President, Steel Structures Technology Center, Inc., Howell, MI, USA*
[2] *Senior Principal, Degenkolb Engineers, San Francisco, CA, USA*
Email: rshaw@steelstructures.com, malley@degenkolb.com

ABSTRACT

Major revisions and additions were made in 2005 to connection design and construction requirements in the American Institute of Steel Construction Seismic Provisions for Structural Steel Buildings (AISC 341). A new AISC standard entitled Prequalified Connections for Special and Intermediate Steel Moment Frames for Seismic Applications (AISC 358) was published with details for reduced beam section connections and extended end plate moment connections. The American Welding Society issued a new welding standard entitled Structural Welding Code - Seismic Supplement (AWS D1.8). The three standards were closely integrated to provide comprehensive materials requirements, design procedures, construction techniques and details, and quality assurance provisions. Specific issues include steel and weld material notch toughness and other properties, welding procedure limitations, areas where certain joint details must be used, weld access holes, areas that must be protected from unapproved welds and other attachments, visual inspection and nondestructive testing mandates, and methods of repair. Currently, these three standards are undergoing updates based upon the experience gained in the use of these standards, and further study and research into several additional bolted, welded and hybrid connection types.

KEYWORDS

Structural Steel, Seismic Design Provisions, Seismic Supplement, Steel Connections, AISC, AWS

1. INTRODUCTION

Major revisions and additions were made in 2005 to connection design and construction requirements in the American Institute of Steel Construction Seismic Provisions for Structural Steel Buildings (AISC 341). A new AISC standard entitled Prequalified Connections for Special and Intermediate Steel Moment Frames for Seismic Applications (AISC 358) was published with details for reduced beam section connections and extended end plate moment connections. The American Welding Society issued a new welding standard entitled Structural Welding Code - Seismic Supplement (AWS D1.8). The three standards were closely integrated to provide comprehensive materials requirements, design procedures, construction techniques and details, and quality assurance provisions. Specific issues include steel and weld material notch toughness and other properties, welding procedure limitations, areas where certain joint details must be used, weld access holes, areas that must be protected from unapproved welds and other attachments, visual inspection and nondestructive testing mandates, and methods of repair. Currently, these three standards are undergoing updates based upon the experience gained in the use of these standards, and further study and research into several additional bolted, welded and hybrid connection types.

2. PREQUALIFIED CONNECTIONS

Following the Northridge Earthquake of 1994, the Federal Emergency Management Agency (FEMA) funded a research project and published recommendations coordinated by the SAC Joint Venture, presenting the results of numerous full-scale tests to establish several types of connections for consideration as “prequalified,” waiving the requirements for individual connection testing. These tests were supplemented with privately funded tests conducted for specific projects, as well as other research efforts. To be considered prequalified for use in Special Moment Frames (SMF) or Intermediate Moment Frames (IMF), the connection must be capable of providing the interstory drift levels in Table 1 below, without brittle fracture and without substantial loss of strength. If the connection is to be used beyond the prescribed limits of prequalification, testing would be required. Moment frames designated Ordinary Moment Frames (OMF) need not be tested, but must follow prescriptive designs and details based upon SMF and IMF requirements, and are limited by building codes to low-rise, lightly-loaded buildings.

Table 1. Classification of moment resisting frames

Moment frame classification	Qualifying drift angle capacity (radians)
SMF Special Moment Frame	0.04
IMF Intermediate Moment Frame	0.02
OMF Ordinary Moment Frame	untested

In 2002, the AISC formed the Connections Prequalification Review Panel, as cited by the AISC Seismic Provisions for Structural Steel Buildings, Appendix P, to review research and publish standards for the analysis, design, fabrication, construction and inspection of connections for moment frames. Three moment connections were selected for inclusion in a new standard entitled Prequalified Connections for Special and Intermediate Steel Moment Frames for Seismic Applications, commonly referred to as AISC 358. Additional connections are expected to be added to the standard in a Supplement in late 2008, as listed in Table 3. Each connection has specific limits for their use as a prequalified connection. Examples of the limits of prequalification provided in AISC 358 for RBS connections include those stated in Table 2.

Table 2. Limits of prequalification for RBS (Reduced Beam Section) moment connections

Property	Limit of prequalification
Beam depth	W920 nominal section, maximum
Beam weight	447 kg/m, maximum
Beam flange thickness	44.5 mm, maximum

Table 3. Prequalified moment connections, and connections under consideration

Acronym	Connection Description	Status	Notes
RBS	Reduced Beam Section	Prequalified 2005	Radius cut trimming of beam flanges Field weld beam flanges to column Field weld or field bolt beam web to column
BSEEP	Bolted Stiffened Extended End Plate	Prequalified 2005	Shop weld end plates to beam web and flanges Field bolt end plates to column
BUEEP	Bolted Unstiffened Extended End Plate	Prequalified 2005	Shop weld end plates to beam web and flanges Field bolt end plates to beam
WFP	Welded Flange Plate	Supplement 2008	Shop weld flange plates to column Field weld flange plates to beam flanges Field weld beam web to column
BFP	Bolted Flange Plate	Supplement 2008	Shop weld flange plates to column Field bolt beam flanges to flange plate Field bolt beam web to column
WUF-W	Welded Unreinforced Flange - Welded Web	Supplement 2008	Field weld beam flanges to column Field weld beam web to column
KBB	Kaiser Bolted Bracket ™	Supplement 2008	Patented, cast steel brackets Shop weld or bolt brackets to beam flanges Field bolt brackets to column
WUF-B	Welded Unreinforced Flange - Bolted Web	under review	Field weld beam flanges to column Field bolt beam web to column
DST	Double Split Tee	under review	Partially restrained connection Shop bolt tees to beam flanges Field bolt tees and web to column

Under FEMA recommendations, columns were previously limited to 300 or 360 mm nominal depth, oriented in the strong axis. In AISC 358, it is now permitted to use other column profiles and deeper sections, depending upon the moment connection type. As an example, for RBS connections, column depths can be rolled shapes up to nominal 920 mm, can be built-up plate columns of the same depth, can be cruciform columns, or can be built-up box columns of 920 mm depth and 600 mm width, unless the column is bi-axially loaded, in which case the column may not exceed 600 mm in both depth or width.

3. STRUCTURAL STEELS

The steel beam materials permitted for use in prequalified moment connections are limited to nominal 345 MPa minimum specified yield stress steels, except for OMF applications which permits steels to a nominal 380 MPa minimum specified yield stress. The preferred steel is ASTM A992, a steel specification adopted in 1998 that provides better control of mechanical properties and a more restricted composition for better weldability and inherent notch toughness. Column sections may of the same or higher strength steels up through 450 MPa minimum specified yield stress. Based upon the steel notch toughness levels present in successful full-scale connection testing, and engineering judgement, 27 J @ +20^{o}C Charpy V-notch (CVN) toughness in the structural steel is considered adequate for performance demands. Because it was determined using mill data and statistical analysis that modern steel production practices for sections with thin flanges consistently provide high reliability in providing at least 27 J of CVN toughness, no notch toughness testing is required except for heavy sections with a flange or web thickness exceeding 38 mm.

4. WELDING FILLER METALS

Filler metal strength is selected on the basis of matching or moderately exceeding the nominal yield stress of the base metal, therefore E480 tensile strength electrodes are selected for both 345 MPa and 380 MPa yield stress steels. Filler metals, under the AISC Seismic Provisions, must have a minimum CVN toughness of 27 J @ -20^{o}C, using the AWS A5 filler metal classification. Based upon fracture mechanics evaluations, small-scale specimen testing and large scale testing results , certain welds designated “demand critical” must undergo a qualification test to establish that the filler metal, when welded with a range of production welding procedures, will achieve a weld deposit CVN toughness of at least 54 J @ +20^{o}C, as well as specified minimum elongation and tensile strength. Because the weld region cooling rates affect the mechanical properties of strength, ductility and notch toughness, the qualification test protocol uses a low heat input and high input value for the given electrode, with a related range of low and high preheat and interpass temperatures. Additionally, all “demand critical” welds must have a minimum CVN toughness of 27 J @ -30^{o}C, rather than 27 J @ -20^{o}C, using the AWS A5 filler metal classification.

To reduce the risk of hydrogen-assisted cracking, welding electrodes and electrode-flux combinations must meet the requirements for H16 (16 mL maximum diffusible hydrogen per 100 grams deposited weld metal. Additionally, to further reduce the risk of hydrogen-assisted cracking in “demand critical” welds, Flux-Cored Arc Welding (FCAW) wires are to be provided in packaging that limits the ability of the electrode to absorb moisture. After removal from protective packaging, the atmospheric exposure time of FCAW electrodes is limited to that provided in the manufacturer's guidelines, established by a special testing protocol.

Studies indicate that when self-shielded FCAW (FCAW-S) filler metals are used in combination with filler metals for other processes, including gas-shielded FCAW (FCAW-G), notch toughness may be reduced in the area of weld metal intermixing in the weld joint. This is possible even though both filler metals may individually produce notch-tough welds. Therefore, notch toughness testing must be conducted prior to the use of FCAW-S filler metals mixed with those of other welding processes, within individual weld joints, to verify that the intermixed region will retain adequate notch toughness.

5. WELDING PROCEDURE SPECIFICATIONS

To maintain heat-affected zone (HAZ) notch toughness, the maximum preheat and interpass temperature is not permitted to exceed 290^{o}C, measured at a distance of between 25 mm and 76 mm from the joint. For minimum preheat and interpass temperatures, existing AWS D1.1 provisions are considered adequate.

With a partial or full loss of gas shielding, porosity is increased and notch toughness may be severely reduced. To maintain notch toughness, welds made using the gas-shielded welding processes are limited to environments with winds of 5 km/hour or less. Windscreens or other shelters may be used to shield the welding operation from excessive wind.

6. WELDED JOINT DETAILS

In the AISC Seismic Provisions, moment connections are designed based upon developing the strength of the beam member, not based upon service loads or factored loads. In order to minimize stress concentrations, thereby reducing the demand for material notch toughness, several very specific welded joint details must be used in order to provide satisfactory seismic performance. These provisions include an improved weld access hole, limitations and treatment, including removal, of weld tabs and backing, and the use of reinforcing fillets in selected locations. Additional details for production are provided in the AWS Structural Welding Code - Seismic Supplement, D1.8:2005.

6.1 Backing Treatment at Beam Bottom Flange

Because of severe tensile stress and strain at the beam bottom flange, where backing is used under CJP groove welds between the beam bottom flange and the column, the backing must be removed, thereby removing the inherent notch created by the backing-column interface. Following the removal of this backing, the root pass is backgouged to sound weld metal and backwelded, with a reinforcing fillet added. The reinforcing fillet has minimum vertical leg of 8 mm, and the horizontal leg of the fillet adjacent to the beam flange is sized such that the fillet toe is located on base metal.

6.2 Backing Treatment at Beam Top Flange

Because of partially offsetting global and local forces and deformations, the tensile stress and strain at the beam top flange is less severe than that at the beam bottom flange. Where steel backing is used under CJP groove welds between the beam top flange and the column, the backing is not removed, and the backing is attached to the column by a continuous 8 mm fillet weld on the edge below the CJP groove weld backing. No fillet or tack weld is permitted between the backing and the beam flange. This would create a new weld toe stress concentration in the beam flange, and would increase the stress at the internal notch at the root of the weld created by the remaining steel backing.

6.3 Weld Tabs

To address poor quality at weld start and stop locations, weld tabs of minimum 25 mm length must be used for weld initiation and termination at joint ends of groove welds. Following completion of welding, weld tabs are removed flush with the edges of the beam flanges and continuity plates. The weld is permitted to widen up to 3 mm beyond the beam flange edge, and up to 6 mm beyond continuity plates edges. In addition, surface quality requirements apply to the weld ends.

6.4 Tack Welds

Because of their stress concentration effects, rapid cooling rates and resultant poorer mechanical properties of weld and heat-affected zone, tack welds attaching steel backing and weld tabs must be placed where they will be incorporated into a final weld, benefiting from the partial remelting and tempering effects from the subsequent pass.

6.5 Weld Access Holes

Low-cycle fatigue failures in beam flanges at the intersection of the weld access hole and the beam flange occurred in laboratory testing. The weld access hole to beam flange intersection angle was steep, creating a high stress concentration at this point. A new weld access hole detail was developed, providing a smoother transition to reduce the stress concentration, and providing a larger opening for welder access and inspection.

6.6 Protected Zones

Inelastic behavior is expected to provide absorption of seismic energy. Plastic hinges are anticipated to form in specific locations in the beam, or yielding to occur in certain types of brace members and in their connections. Because attachments and stress concentrations in the vicinity of the plastic hinge or yielding area may initiate fracture, this area is designated a “protected zone.” Welded shear studs, and decking attachments that penetrate a beam flange such as screws and shot-in pins, may not be placed on beam flanges within the protected zone. Decking arc spot welds (puddle welds) as required to secure decking are permitted. Welded, bolted, screwed, or shot-in attachments for perimeter edge angles, exterior facades, partitions, duct work, piping or other construction are also prohibited within protected zones.

6.7 k-Area

The “k-area” is the region within 38 mm of the "k-line" on the rolled shape web. The “k-line” is the location where the roll radius between web and flange intersects the web. The k-area is known to have severely reduced notch toughness caused by cold-working during the steel mill process known as rotary straightening, used to straighten rolled sections to within specified tolerances. Although welding to these areas is not prohibited, it is discouraged through a variety of details, and if welding is performed in this area, nondestructive examination following welding is required to verify the member web to be crack-free.

7. VISUAL AND IN-PROCESS WELDING AND BOLTING INSPECTION

An extensive list of welding and bolting inspection tasks is provided in the 2005 AISC Seismic Provisions, Appendix Q, divided into the sequences of “before welding,” “during welding” and “after welding.”, and similar sequences for bolted connections. Inspection tasks are assigned to both quality control (fabrication and erection) personnel and quality assurance (owner’s representative) personnel. Most items are assigned “observe” status, with that specific inspection task done on a random, daily basis. Other items are assigned “perform” status, which requires that the welded or bolted connection receives such inspection before final acceptance.

8. NONDESTRUCTIVE EXAMINATION (NDE) OF WELDED CONNECTIONS

The AISC Seismic Provisions contains prescriptive NDE requirements based upon the type and location of weld. All welds are evaluated on the basis of the static, non-tubular provisions of AWS D1.1. NDE is performed using ultrasonic testing (UT), magnetic particle testing (MT), or both in combination. Because of the detrimental effects of surface and near-surface discontinuities on the performance of welds in high plastic strain regions, MT is used. UT is used to detect significant embedded flaws. Some reduction in the frequency of NDE is permitted for some categories when a given welder has established a low rejection rate for the project. AWS D1.8 provides details on the qualifications of the inspectors and NDE technicians, the techniques of the inspections and examinations, and additional details on the acceptance criteria. The requirements for NDE of welded joints in the seismic force resisting system are summarized in Table 4.

Table 4. NDE Requirements for Seismic Load Resisting System Welded Connections

Weld or location	NDE Required
CJP groove welds	UT is performed on 100% of CJP groove welds in materials 8 mm thick or greater. MT is performed on 25 percent of all beam-to-column CJP groove welds.
Base metal for laminations and lamellar tearing	After joint completion, base metal thicker than 38 mm, loaded in tension in the through-thickness direction in tee and corner joints, where the connected material is greater than 19 mm and contains CJP groove welds, is examined by UT for discontinuities behind and adjacent to such welds. Any discontinuities found within the top one-fourth of the thickness of the welded steel surface are evaluated.
Beam copes and weld access holes	At welded splices and connections, for those cases where the beam flange thickness exceeds 38 mm for rolled shapes, or when the beam web thickness exceeds 38 mm for built-up shapes, thermally cut surfaces of beam copes and weld access holes are examined using MT or penetrant testing (PT).
k-area	If welding of doubler plates, continuity plates or stiffeners has been performed in the k-area of a rolled shape, the member web is examined for cracks using MT. The examination area includes the k-area base metal within 75 mm of the weld. This examination is to be performed no sooner than 48 hours after completion of welding.
Weld tab removal sites	At the ends of beam-to-column moment connection joints, after weld tab removal, the weld ends are examined using MT.

9. SUMMARY

Unexpected connection failures during the 1994 Northridge Earthquake in the USA and the 1995 Great Hanshin (Kobe) Earthquake in Japan led to extensive research and testing to develop reliable connections, seeking to provide building safety in new and existing steel-framed buildings. In the USA, problems in existing moment connections included inadequate analysis approaches, main member material properties, inadequate weld metal notch toughness, details that created inherent stress concentrations and severe notch effects, poor adherence to proper welding and inspection practices, and inadequate nondestructive testing techniques and practices.

New seismic connection and welding standards have been developed and implemented by the American Institute of Steel Construction (AISC) and the American Welding Society (AWS). Within AISC, a variety of standardized connections have been developed based upon full-scale tests to provide safe, reliable, economic beam-column moment connections that are fully welded, fully bolted, or a combination of the two. These moment connections include direct-welded beam flanges, reduced beam flange widths, welded flange plates, bolted end plate connections, and bolted T-stub connections, as well as patented connections. In addition to the use of these prescriptive connections, detailed requirements for materials properties, construction quality, inspection and nondestructive testing are provided. New requirements for other connections such as column splices, bracing systems and gusset plates have been added, as well as controls on plastic hinging regions. The AWS has additional and more specific details for welded connections, weld access holes, welding materials testing requirements, enhanced performance testing of welders, enhanced techniques and skills testing for nondestructive examination technicians, and provisions for a variety of weldment repairs.

REFERENCES

AISC (2005), Seismic Provisions for Structural Steel Buildings, AISC 341-05, American Institute of Steel Construction, Chicago IL, USA

AISC (2005), Prequalified Connections for Special and Intermediate Steel Moment Frames for Seismic Applications, AISC 358-05, American Institute of Steel Construction, Chicago IL, USA

AWS (biannual), Structural Welding Code – Steel, AWS D1.1/D1.1M, American Welding Society, Miami FL, USA

AWS (2005), Structural Welding Code – Seismic Supplement, AWS D1.8/D1.8M, American Welding Society, Miami FL, USA

FEMA (2000), Recommended Seismic Design Criteria for New Steel Moment-Frame Buildings, FEMA 350, Federal Emergency Management Agency, Washington DC, USA

FEMA (2000), Recommended Specifications and Quality Assurance Guidelines for Steel Moment-Frame Construction for Seismic Applications, FEMA 353, Federal Emergency Management Agency, Washington DC, USA

FEMA (2000), State of the Art Report on Welding and Inspection, FEMA 355B, Federal Emergency Management Agency, Washington DC, USA

FEMA (2000), State of the Art Report on Connection Performance, FEMA 355D, Federal Emergency Management Agency, Washington DC, USA

Johnson, M.Q, Mohr, W. and Barsom, J. (2000), SAC Joint Venture, Evaluation of Mechanical Properties in Full-Scale Connections and Recommended Minimum Weld Toughness for Moment Resisting Frames, SAC/BD-00/14, SAC Joint Venture, c/o Applied Technology Council, Redwood City CA, USA

Johnson, M.Q. (2000), SAC Joint Venture, Evaluation of the Effect of Welding Procedure on the Mechanical Properties of FCAW-S and SMAW Weld Metal Used in the Construction of Seismic Moment Frames, SAC/BD-00/12, SAC Joint Venture c/o Applied Technology Council, Redwood City CA, USA

Mohr, W. (1999), Weld Acceptance Criteria for Seismically-Loaded Welded Connections, SAC/BD-99/24, SAC Joint Venture c/o Applied Technology Council, Redwood City CA, USA

Ricles, J.M., Mao, C., Lu, L-W. and Fisher, J.W. (2000), Development and Evaluation of Improved Details for Ductile Welded Unreinforced Flange Connections, SAC BD 00-24 2000, SAC Joint Venture c/o Applied Technology Council, Redwood City CA, USA