Steel Special Moment Frames

Connection Seismic Requirements

By Scott M. Adan, Ph.D., S.E., SECB and Ronald O. Hamburger, S.E., SECB

In regions of high seismic risk, severe earthquakes are rare events, affecting typical building sites at intervals of hundreds of years. Given the infrequent return period, it is economically impractical to design structures to resist such rare but severe earthquakes without damage. Instead, building codes have developed a design philosophy intended to protect life safety by avoiding earthquake-induced collapse in severe events, while permitting extensive structural and nonstructural damage.

In a steel special moment frame, it is intended that inelastic behavior be accommodated through the formation of plastic hinges at beam-column joints and column bases. Plastic hinges form through flexural yielding of beams and columns and shear yielding of panel zones. Large cyclic plastic deformations of steel shapes inevitably results in local buckling of the section. Severe local buckling, such as that shown in *Figure 1*, results in strength loss and, for this reason, it is desirable to avoid plastic hinging in columns. The connections must be capable of transferring moment and shear forces that can be developed in the beam to the column. As a result of material and system overstrength, these moment and shear forces can be substantially larger than the design forces specified by the building code.

As part of its support for the National Earthquake Hazards Reduction Program (NEHRP), the National Institute of Standards and Technology (NIST) is developing a series of technical briefs to assist in improving seismic design and construction productivity. Technical Brief No. 2, entitled, *Seismic Design of Steel Special Moment Frames: A Guide for Practicing Engineers*, addresses the design, specification, and construction of steel special moment frames. This article, the second of two, contains excerpts from several sections of the brief including provisions associated with the seismic design of moment frame connections. The first article, appearing in the June 2010 issue of STRUCTURE magazine, presented an introduction to the steel special moment frame with a perspective on its historic development.

Connection Selection

Since the 1994 Northridge Earthquake, the building code has required that steel special moment connections be demonstrated capable of developing at least 0.04 radians of interstory drift without excessive strength loss, when subjected to a prescribed cyclic loading protocol. This qualification testing must be conducted on full-size specimens using sections, materials, and fabrication procedures comparable to those to be incorporated in the actual construction. Relatively few laboratories have the capability to perform such tests, and the tests are expensive, even if successful. If initial connection designs fail the testing, it may be necessary to perform multiple iterations of the design and testing, adding months of delay and hundreds of thousands of dollars of expense to projects. To avoid these difficulties, the code permits the use of prequalified connections. Prequalified connections have been demonstrated by extensive testing and analysis, acceptable to an expert review panel, to be capable of reliable service when used within specified limits. There are several sources of connection prequalifications.

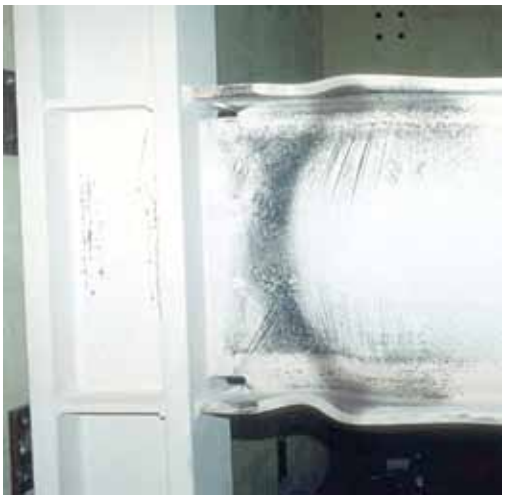

Figure 1: Connection local buckling of beam flanges and web at high levels of inelastic rotation. Courtesy of Michael D. Engelhardt.

AISC Prequalified Connections

The American Institute of Steel Construction (AISC) maintains a Connection Prequalification Review Panel (CPRP) that develops an American National Standards Institute (ANSI)-approved standard, AISC-358 *Prequalified Connections for Special and Intermediate Moment Resisting Frames for Seismic Applications*. AISC 358 presents materials, design, detailing, fabrication and inspection requirements for a series of prequalified moment-connection details. This standard is referenced by the code, and connection prequalifications contained in the standard are acceptable to most building officials. AISC updates and reissues this standard from time to time, as additional research becomes available. The connections in AISC 358 are not interchangeable; there are limits of applicability for each. *Figure 2* through *Figure 6, page 12* show the configuration of connection technologies currently included in AISC 358.

Other Prequalified Connections

In addition to AISC 358, several other sources of prequalification exist. The federally-funded SAC Joint Venture that performed the post-Northridge earthquake research into steel moment frame behavior published FEMA 350 – *Recommended Design Criteria for Moment Resisting Steel Frames*, which contains a number of connection prequalifications. Many of the FEMA 350 prequalifications have since been updated and adopted into AISC 358. Some have not, either because the CPRP has deemed that there was not sufficient research to support the prequalification or it has not had time to review the connection and include it in AISC 358. FEMA 350, like AISC 358, includes design, materials, fabrication, and inspection criteria for prequalified connections. When both AISC 358 and FEMA 350 have criteria for a particular connection type, the information in AISC 358 should be considered to supersede that in FEMA 350. Some, but not all, building officials will accept FEMA 350 prequalifications.

In addition, there are several code agencies that operate evaluation services to qualify the use of proprietary products and procedures as meeting the criteria contained in the building code. These evaluation services publish connection prequalifications for proprietary connection technologies in the form of evaluation reports, and building officials typically accept these reports as evidence of code conformance. However, engineers relying on these evaluation reports should be aware that the rigor of review does not always match that performed by AISC's CPRP. Therefore, the performance capability of connections that have been included in these reports may not match that of connections contained in AISC 358.

Some individual patent holders for proprietary connections maintain their own library of test data and analysis to

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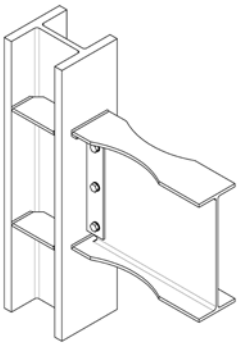

Figure 2: Reduced beam section (RBS) connection.

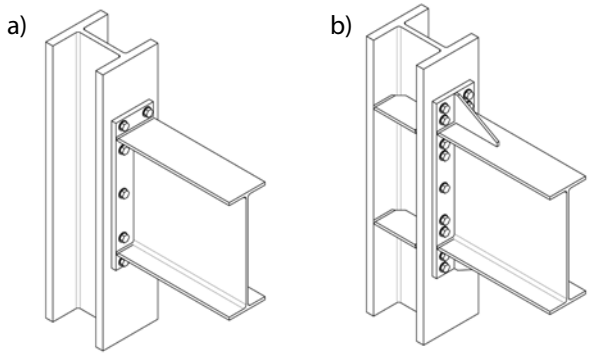

Figure 3: Bolted (a) unstiffened (BUEEP) and (b) stiffened (BSEEP) extended end plate connections.

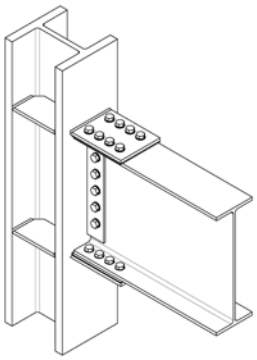

Figure 4: Bolted flange plate (BFP) connection.

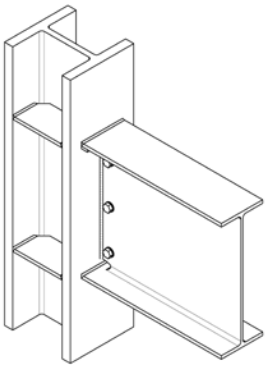

Figure 5: Welded unreinforced flange – welded web (WUF-W) connection.

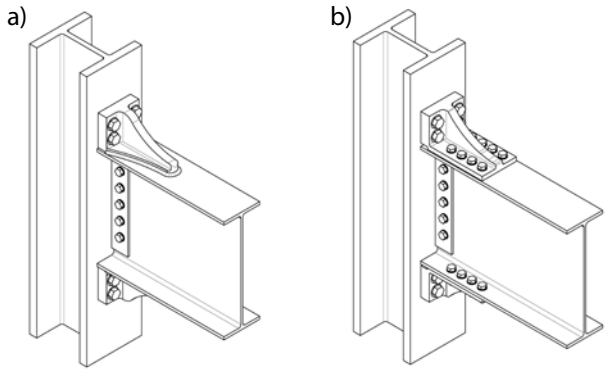

Figure 6: Kaiser bolted bracket (KBB) connection (a) welded and (b) bolted to the beam.

substantiate the performance capability of their connections. Strictly speaking, these connections are not prequalified. However, some building officials will accept their use, sometimes requiring independent review as a condition of such use.

Project Specific Qualification

In some cases, the prequalifications available in AISC 358, FEMA 350 and evaluation service reports may not be adequate to cover the design conditions for a particular project. One reason this may occur is that the sizes of selected moment frame elements may fall outside the limits contained within the prequalifications. Another reason this may occur is that presently there are no prequalifications associated with connections to the minor axis of wide-flange columns. If no prequalified connections meet the requirements of a particular design condition, the code requires performance of project-specific testing. At least two specimens must be tested and must pass the prescribed criteria. Since the required size of the connection specimens can be quite large, often only universities have the capability to perform such testing. Scheduling of these facilities can be difficult. Therefore, if project-specific testing will be required, early planning for this effort is recommended. In consideration of the specimen fabrication, shipping, and set-up costs, testing can be expensive. Therefore, consideration should be given to using framing configurations that will enable the use of prequalified connections.

All of the existing prequalification tests have been conducted using specimens in which the beams and columns were within a single plane, and in which the beams intersected the columns orthogonally. Prequalifications do not presently exist for connections in which the beams are skewed relative to the axis of the column, are connected at other than orthogonal conditions, or are part of a column subjected to bi-axial frame behavior. For these conditions, the code requires connection-specific qualification. Therefore, it is probably best to avoid these conditions when laying out the structure's seismic force-resisting system.

Summary

Historically, steel moment frames have exhibited superior performance when subjected to earthquake ground shaking. The system is designated as special when the frame incorporates design provisions capable of withstanding significant inelastic deformations during large seismic events. Since the 1994 Northridge Earthquake, building codes have required that special moment connection performance be demonstrated through qualification testing, but this testing can be avoided through the use of prequalified connections. Project specific qualification is occasionally required when connection configurations fall outside the limits contained in published connection prequalification reports.

Further information on the design of steel special moment frame connections is contained in the NEHRP Technical Brief No. 2. The brief also provides information on the expected earthquake performance of moment frame systems in general, and outlines applicable building code design criteria. The intent of the document is to emphasize code requirements and accepted approaches to their implementation. It provides background information and illustrations to help understand the requirements. The brief was developed by the NEHRP Consultants Joint Venture (a partnership of the Applied Technology Council and Consortium of Universities for Research in Earthquake Engineering), under Contract SB134107CQ0019, Earthquake Structural and Engineering Research, issued by the National Institute of Standards and Technology. It is available as a free download at:

www.nehrp.gov/pdf/nistgcr9-917-3.pdf

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Scott M. Adan, Ph.D., S.E., SECB is a Consulting Structural Engineer in the San Francisco Bay area. Dr. Adan is the SEAONC Steel Subcommittee chair and is a member of both the Connection Prequalification Review Panel and the Committee on Manuals for AISC. He can be reached at ***scott.adan@gmail.com****.*

Ronald O. Hamburger, S.E., SECB is Head of Structural Engineering, Western Region for Simpson Gumpertz & Heger Inc. in San Francisco. Mr. Hamburger is Chair of the AISC Connection Prequalification Review Panel and received the Institute's Higgins award in 2006. He can be reached at ***ROHamburger@sgh.com****.*