A Guide To High-Strength Bolting

An overview of the rules for snug-tight bearing, tightened bearing and slip-critical connections

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WHEN HIGH-STRENGTH BOLTING FIRST BEGAN REPLACING RIVETING MORE THAN THREE DECADES AGO, all of the research that led to the initial rules (allowable stresses) consisted of connections assembled with highly tensioned bolts. The thinking at the time was to create a connection that was resistant to slip and therefore resistant to fatigue failure.

The rules were first published with a required pretension for all applications—static as well as dynamic loading. The only difference between a fatigue resistant connection and a statically loaded one was that the former had certain restrictions on the faying surfaces so they would not be too slippery and the specified allowable shear value was lower so more bolts were required. This fatigue resistant application was termed a "friction" connection.

As research continued, the shear strength of a high-strength bolt was increased considerably. However, because all of the tests were on fully tightened bolts, "snug-tight" bolts were not considered valid for many years. Ultimately, the Research Council on Structural Connections (RCSC) agreed to debate this concept (at its annual meeting in 1982). It was pointed out that A307 bolts were not tensioned, so why should high-strength bolts be required to be tensioned in the same applications that untensioned A307 bolts were permitted? The council ultimately agreed and "snug-tight" high-strength bolts were permitted in the same applications where A307 bolts were permitted. Applications where "snug-tight" high-strength bolts are not permitted are:

- Column splices in all tier structures 200-ft. or more in height
- Column splices in tier structures 100- to 200-ft. in height if the least horizontal dimension is less than 40% of the height
- Column splices in tier structures less than 100-ft. in height if the least horizontal dimension is less than 25% of the height
- In structures over 125-ft. in height for connections of all beams and girders to columns and of any other beams and girders on which the bracing of columns is dependent
- In all structures carrying cranes of more than five-ton capacity (roof truss splices and connections to columns; column splices, column bracing, knee braces and crane supports)
- Connections for supports of running machinery or of other live loads that produce impact or reversal of stress

The next development in a slip-critical (friction) connection was the introduction of different allowable shear values as a function of the coefficient of friction between the faying surfaces, which is primarily a function of the coating. At this point, it should be pointed out that a slip-critical (SC) connection and a shear-bearing connection with the same number of bolts both have the same ultimate shear value. A SC connection is a connection designed primarily for fatigue at service loads. In this respect, AISC Specification Section K4 states: "The occurrence of full design wind or earthquake loads is too infrequent to warrant consideration in fatigue design."

There basically are only two reasons for specifying an SC connection:

- Increase fatigue resistance (at service loads) and
- Prevent slip prior to ultimate load because of concern that such slip might change the geometry of the structure and affect the analysis

Slip usually occurs between 1.2 and 1.4 times service load whereas ultimate load is usually 1.5 or more times the service load.

The question remains as to where slip-critical connections should be required. The basic application is, of course, where fatigue is a factor. While the common case is in bridge design, it is not usually a consideration in building work. This is because it takes 20,000 loading cycles, as a minimum, for fatigue to be a factor and this is rare in building structures.

Even in non-fatigue applications, though, engineers have for some time questioned if slip-critical high-strength bolted connections should not be used in the various connections of bracing members and moment connections in the design of lateral force-resisting frames. The ASCE Committee on Steel Building Structures studied the question and their report follows:

ASCE Committee Report

In steel building construction, lateral loads generated by wind or earthquake are typically resisted by moment-resistant frames or braced frames. The connections between major elements of these frames can be designed as fully welded, fully bolted or a combination of welded and bolted. Under certain circumstances, where bolts are to be employed, the use of slip critical (SC) design values may be required to provide acceptable performance of these connections.

Discussion and Recommendations

The following discussion will provide recommendations for bolted connections, regarding the use of SC or bearing bolt values. Four different situations will be treated separately in this discussion:

Case 1: Moment-Resisting Beam-Column Connections in Frames Designed to Resist Wind Loads

Case 2: Moment-Resisting Beam-Column Connections in Frames Designed to Resist Seismic Loads

Case 3: Diagonal Brace Connections in Frames Designed to Resist Wind Loads

Case 4: Diagonal Brace Connections in Frames Designed to Resist Seismic Loads

Present codes (ICBO 1991, for instance) require consideration of both seismic and wind design forces for buildings in most regions of the U.S. Connection design for these two load conditions differs in that wind design typically assumes elastic response, whereas seismic design implicitly considers inelastic action under actual earthquake forces. In the design of buildings in seismic regions, lateral force-resisting connections are detailed to meet the seismic design provisions, even though wind forces may be the controlling load condition. This is done to assure the ductile response of these connections under actual earthquake forces, which are expected to be much larger than the code-prescribed values.

It also should be noted that for some conditions in the following discussion, bearing connection designs are suggested for wind loading while SC connections are recommended for seismic forces (for example, girder web connections in moment-resisting beam-column connections). In these cases, the designer must check both loading conditions because there are significant differences between the allowable design forces for bearing and for SC bolts. Conditions may occur where the number of bolts in a connection is controlled by the seismic forces even though the wind loads on the connection are higher.

Case 1: Moment-Resisting Beam-Column Connections in Frames Designed to Resist Wind Loads. (The discussion related to moment-resisting beam-column connections will address bolted girder flange and web connections separately.)

Girder Web Connection—For the girder web connection that consists of a shear tab (or pair of angles) that is welded to the column and bolted to the beam, shear forces are transferred through friction and/or bearing between the connecting plates. Where high shear forces occur, the bolts can slip into bearing, transferring a portion of the shear into the flange connections. This type of force transfer should be avoided because the flange connections are not typically designed for such out-of-plane forces. In such cases, it is advisable to design the connections with SC bolts.

Monotonic testing at Lehigh University indicated satisfactory performance of joints with single web connection plates and the bolts designed in bearing (J.S. Huang, W.F. Chen, and L.S. Beedle—1973: "Behavior and Design of Steel Beam-to-Column Connections," WRC Bulletin No. 188, Welding Research Council). It would appear, then, that the web bolts can be designed in bearing if the designer can demonstrate that the shear forces resulting from wind loads are so small that repeated slip can not occur. This could be accomplished by recognizing that fully pretensioned bolts slip at a load of 1.2 and 1.4 times the SC allowable values. If bearing connections are used, they should be fully tightened to meet the pretension requirements of Table J3.7 of the AISC Specification (ASD *Manual of Steel Construction*—1989).

Girder Flange Connections—For a girder flange connection to a flange plate that is welded to the column flange, slip of the bolts into bearing under wind loads will result in increased story drifts. For standard round holes (bolt diameter plus $^1/_{16}$ in.), the amount of this increased drift could be minor, and bearing connections may be acceptable. An evaluation of the impact of this increased drift may be necessary for buildings especially sensitive to lateral displacements. If bearing connections are used, they should be fully tightened to meet the pretension requirements of Table J3.7 of the AISC Specification (ASD *Manual of Steel Construction*—1989). If slotted holes are employed, SC connections must be used.

Case 2: Moment-Resisting Beam-Column Connections in Frames Designed to Resist Seismic Loads

Girder Web Connection—In areas of high seismicity, most moment-resisting beam-column connections consist of full-penetration welding of the flanges and high-strength bolting of the web. Seismic design differs from wind design in that inelastic action of the frames is assumed under the code-specified loading. In most cases, the beam-column connections are designed to force yielding in the beams and/or the column web panel zone. Tests at the University of California-Berkeley have shown that bolted web connections, which are subjected to a number of cycles that cause slipping of the bolts into bearing, can transfer shear forces large enough to result in failure of the girder flange welds (E.P. Popov—1983: "Seismic Moment Resisting Connections for Moment-Resisting Steel Frames," UCB/EERC-83/02, University of California-Berkeley). As a result, the 1991 Uniform Building Code and the AISC Seismic Provisions for Structural Steel Buildings (1992) both require that the web be connected by means of welding or using SC connections for special moment-resisting frames.

Girder Flange Connections— Recent tests at the University of California-Berkeley have shown that beam-column moment connections with flange plates, designed in accordance with recommendations of the AISC Manual of Steel Construction, demonstrate acceptable ductility (A. Astaneh and James D. Harriott—1990: "Cyclic Behavior of Steel Top- and Bottom-Plate Moment Connections," UBC/EERC-90/19, University of California-Berkeley). In this case, standard holes should be used; either SC or fully tightened bearing connections would be acceptable.

Other connections methods or details (for both web and flange connections) are allowed if they can be demonstrated by test to develop the bending strength of the beam or the moment resulting from the nominal shear strength of the panel zone, or by calculations to develop 125% of the design strength of the beam or the moment resulting from the nominal shear strength of the connected elements. A less restrictive requirement may be used for ordinary moment-resisting frames in some cases.

Case 3: Diagonal Brace Connections in Frames Designed to Resist Wind Loads

In order to facilitate erection, bolted diagonal brace connections often are designed with slotted holes. In this case, the Specification requires SC connections. If standard holes are used, bearing bolts may be used, since any additional story drift caused by bolts slipping into bearing is likely to be insignificant. (A study by Michael I. Gilmor of the Canadian Institute of Steel Construction confirms this conclusion, i.e., slippage of bolts to standard holes does not contribute appreciably to story drift. Gilmor calculated the drift of a 21-story eccentrically braced frame building assuming that all the connections slipped in the same direction the full amount of difference between bolt and hole size—a statistical impossibility. The resulting P-Delta moments were insignificant in the design of the beams, columns and connections.) If bearing connections are used, they should be fully tightened to meet the pretension requirements of Table J3.7 of the AISC Specification (ASD *Manual of Steel Construction*—1989).

Case 4: Diagonal Brace Connections in Frames Designed to Resist Seismic Loads

Typically, oversized and/or slotted holes should not be used in the design of bolted bracing connections unless the bolts are designed so that the possibility of slip is precluded. This could be accomplished by providing SC bolts that can develop the strength of the members, recognizing that these bolts slip at a load between 1.2 and 1.4 times the allowable design load. If standard holes are used, fully tightened bearing bolts may again be used to develop the forces required by the applicable code.

A research investigation recently performed at the University of California-Berkeley is exploring the energy-dissipation capacity of systems that rely on slipping of tightened bolts in slotted holes (C.E. Grigorian, T.S. Yang and E.P. Popov—1992: "Slotted Bolted Connection Energy Dissipators," UBC/EERC-90-10, University of California-Berkeley). Until design rules that properly control the response of such a system are developed, slotted holes in bracing connections should not be used in seismic design, unless the possibility of slip is precluded.

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